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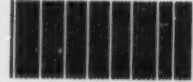
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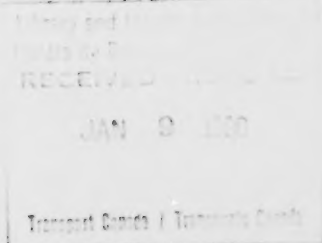
TP 9728E

Precise Radar Integrated Navigation System
(NAVFIX) for Coastal and Inshore Navigation

Prepared for
Transportation Development Centre
Policy and Coordination Group, Transport Canada

by Offshore Systems Ltd.

December 1988



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The contents of this report reflect the views of Offshore Systems Limited and not necessarily the official view or opinions of the Transportation Development Centre of Transport Canada.

Un sommaire en français de ce rapport est inclus avant la Table des matières.

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16. Abstract This project investigated two precise radar positioning concepts and interfaced these systems with an electronic navigation chart display system. The objective was to develop a real-time radar positioning system (NAVFIX) for vessels navigating coastal and inland waters. The principal concept investigated was Polarimetric Radar for Accurate Navigation (PRAN). The PRAN system is able to uniquely discriminate twist reflectors from the background by suppressing the unwanted land clutter. The second concept investigated was the commercially available RADARFIX. The system was modified to utilize circular polarization as the radar discriminant with the same network of twist reflectors. Both systems were interfaced to the Precise Integrated Navigation System (PINS 9000) manufactured by Offshore Systems Limited. The report details the development of NAVFIX, the first dynamic, real-time reflector based radar positioning system.					
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16. Résumé La recherche dont il est rendu compte concerne deux systèmes de radionavigation de précision, intégrés à un système d'affichage électronique de cartes de navigation. Le but de la recherche consistait à mettre au point un système de radionavigation de précision en temps réel NAVFIX, pour la navigation dans les eaux fluviabiles ou littorales. Le système analysé en plus grande profondeur a été le système de radionavigation PRAN capable d'extraire les signaux renvoyés par les réflecteurs du bruit environnant, notamment le clutter terrestre. Quant au second système évalué, il s'agit de celui qui est commercialisé sous le nom de RADARFIX et adapté à la polarisation circulaire, un des procédés servant à la discrimination échos radar. Le même réseau de réflecteurs a servi à l'évaluation de ces deux systèmes, et tous deux ont été intégrés au système de radionavigation PINS 9000, fabriqué par Offshore Systems Limited. Le produit final obtenu appelé NAVFIX constitue le premier système de radionavigation dynamique à réflecteurs, fonctionnant en temps réel.					
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Marine Atlantic provided the M.V. "Atlantic Freighter" as a test platform for the NAVFIX system and funding for the purchase of the prototype radar positioning system. The Canadian Coast Guard provided support for the concept of radar positioning and participation in the project review process. The Communications Research Laboratory provided technical assistance and background information on many aspects of previous research into radar positioning. The Transportation Development Centre provided funding and the Scientific Authority for the project. The Department of Supply and Services supported the NAVFIX development under the Unsolicited Proposals Program (UPP) for which the contractor is most grateful.

PREFACE

The Transportation Development Centre (TDC) of Transport Canada has been supporting research and development directed at improving precise navigation for Canada's inland and coastal waterways. Funded support by TDC in two distinct areas has seen the development of passive polarimetric retro-reflectors by CRL and the development of a Shipboard Integrated Navigation and Display System (SINADS) by OSL.

The NAVFIX (Precise Radar Integrated Navigation) System, submitted to DSS as an Unsolicited Proposal (UP 06-014), proposed to combine two innovative Canadian concepts with an existing radar positioning system (RADARFIX) to create an integrated system which would address the technological problems and unique opportunities applicable to conventional marine operations in Canadian waters.

SUMMARY

Offshore Systems Ltd. (OSL) was tasked by the Transportation Development Centre (TDC) of Transport Canada to develop a prototype precise radar integrated navigation system (NAVFIX) which combined two unique Canadian technologies and a French development. The overall project objective was to develop a system that resulted in a precise vessel positioning system for inshore and coastal waterways. The goals of the radar positioning system development were:

- a) positional accuracies approaching or equivalent to those of existing microwave systems;
- b) position determination from a precision shipboard radar;
- c) utilization of both passive, shore-based polarimetric radar retro-reflectors and natural, identifiable radar targets;
- d) integration of radar positioning data into a real-time electronic navigation chart display system; and,
- e) delivery of a prototype radar positioning system to meet Marine Atlantic's precise vessel positioning requirement for Port Aux Basques, Newfoundland.

The approach taken to attain these goals was to execute a detailed engineering analysis of the target radar positioning systems. The two systems evaluated were the Polarimetric Radar for Accurate Navigation (PRAN) as developed by Communications Research Laboratory (CRL) of Hamilton and the commercially available RADARFIX system by Virkewin of France. Both systems were interfaced to the Precise Integrated Navigation System (PINS 9000) as manufactured by Offshore Systems Ltd. (OSL) for the purpose of recording the radar positioning data and to provide a graphic display on the electronic navigation chart. The PINS 9000 also simultaneously recorded data from other proven positioning systems (Loran-C, Motorola MRS III and Krupp-Atlas Polarfix) to provide accuracy comparisons.

The RADARFIX system, due to its availability, was acquired and analyzed first. The system utilizes the range and bearing data from known radar targets to determine its position. The off-the-shelf RADARFIX system requires a network of radar targets and these targets must be well defined and uniquely identifiable.

The RADARFIX system was installed in OSL's M.V. "OFFSHORE SURVEYOR" in August 1987 and dynamically tested in Vancouver Harbour. After considerable effort, it was determined that a suitable network of radar targets could not be found in Vancouver Harbour.

The RADARFIX system was then tested at Steveston Bend on the Fraser River. This location had numerous radar targets that

were suitable for the RADARFIX system. The accuracy of the system was verified by comparing simultaneous positioning data from the Krupp-Atlas Polarfix system. The results indicated the RADARFIX positioning system provided a static accuracy of 1.77 metres with a standard deviation of ± 0.98 metres.

The results from Steveston Bend were very encouraging but OSL concluded that unless RADARFIX could be made to work at any location then it had limited practical use for many coastal and inland waterways. OSL therefore proceeded to investigate the use of corrugated radar twist reflectors and circular polarization as a means of enhancing the RADARFIX performance. Circular polarization was chosen since it both enhanced the ability to uniquely discriminate twist reflectors from the background by suppressing the unwanted land clutter and that polarization conversion could be accomplished by a simple modification to the existing standard marine radar antenna. Furthermore, a trihedral radar reflector with a corrugated reflection surface of rectangular grooves was found to maintain the sense of the incident circular polarized radar wave and thus provided a coherent, uniquely identifiable radar target for the modified RADARFIX system.

The modified RADARFIX system was tested in Deep Cove in April 1988. Deep Cove is a rugged, sparsely populated section of Indian Arm. A network of corrugated radar reflectors was established and the system performance was verified against a Motorola microwave positioning system. The tests demonstrated that the modified RADARFIX system could utilize a network of radar reflectors and provide accuracy comparable to microwave positioning systems.

The next phase of development for the modified RADARFIX system was to design features in the PINS 9000 that simplified the user interface and eliminated the need to initialize the system from a fixed position. These modifications required a software change by the RADARFIX manufacturer and for the PINS 9000 to download Loran-C position, gyro heading and vessel speed to the modified RADARFIX system. These changes were implemented and this "hands-free" mode was successfully tested in Deep Cove in May 1988.

The Polarimetric Radar for Accurate Navigation (PRAN) as developed by CRL is based upon their previous work with polarimetric radar and twist reflectors. There were three major components within the PRAN development; the polarimetric transmission grid twist reflector, the dual-polarized antenna and the radar system. A subcontract was awarded to MPB Technologies (MPBT) Inc. of Dorval, Quebec to build a cost-effective, environmentally protected twist reflector using the existing CRL transmission grid design

specifications as a guideline. The dual-polarized antenna was developed by Christiaan Huygenslaboratorium (CHL) of the Netherlands. The antenna specifications were also provided by the Communications Research Laboratory.

CRL developed the PRAN radar system by incorporating the components of two separate radars and several custom circuit boards into one enclosure. The system utilized a dual-polarized antenna and a network of the passive twist reflectors to convert the incident radar wave from horizontal to vertical. Accurate range and bearing data are determined for each twist reflector detected in the network.

The resultant radar system was bench tested at CRL and then shipped to OSL in May 1988. The PRAN system was installed in the M.V. "OFFSHORE SURVEYOR" and tests were conducted in June 1988 in Vancouver Harbour. Both static and dynamic tests indicated that the twist reflectors could be detected but not isolated from the background clutter. The PRAN system output range and bearing data for several spurious targets.

The PRAN system was then tested in Deep Cove which has considerable less background clutter than Vancouver Harbour. Under static conditions, the twist reflectors could be isolated from the unwanted background clutter. However, dynamic trials were less encouraging with the PRAN system outputting invalid range and bearing data to several spurious targets.

Preliminary PRAN test results did not clearly demonstrate that cross linear polarization provided a significant advantage over circular polarization as far as clutter suppression. The trials also indicated that more development was required to make the PRAN system an operational prototype radar positioning system. Thus, further investigation of the PRAN system performance with regards to multipath and target detection circuitry were not undertaken.

Another major aspect of the CRL subcontract was the development of PRAN simulation software. The simulation was designed to assist in the selection of reflector sites given the digital terrain model of the area, vessel dynamics (pitch and roll), radar characteristics (power, frequency and pulse repetition factor), reflector characteristics (radar cross section and angular response), and antenna specifications (gain, beamwidth and height). These parameters can then be utilized to ensure reflector sites have line-of-sight, minimal multipath and provide adequate coverage over the area of interest.

In the final analysis of both radar positioning systems, it was clear that only the modified RADARFIX system was able to meet Marine Atlantic's positioning requirements at Port Aux Basques, Newfoundland. Thus, the system was installed in the

M.V. "ATLANTIC FREIGHTER" and a network of twist reflectors was established around the approaches to Port Aux Basques in August 1988. Initial trials, conducted from September through October, found that the system did not provide the desired coverage and it was not able to automatically start-up during approach to Port Aux Basques. These problems were rectified by software modifications and network enhancements in November 1988. The final delivered system is the first dynamic, real-time reflector based radar positioning system.

Further development should concentrate on the application of radar positioning in the St. Lawrence Seaway and other areas where a network of reflectors would provide a practical and economical solution to the need for precise navigation. To this end, OSL recommends the following principal areas for further investigation:

- a) radar reflector design;
- b) reflector network design software;
- c) cross versus circular polarization; and,
- d) simplified shipboard hardware.

Each of these recommendations is discussed in the following paragraphs.

Two unique radar reflector concepts were utilized during the NAVFIX development; the corrugated reflection surface and the polarimetric transmission grid. Both worked well with circular polarization (modified RADARFIX) and cross polarization (PRAN). These two concepts should be investigated with respect to performance (radar cross section and angular response) versus production costs. Additional consideration should be given to installation techniques used to support single and multiple arrays of the radar reflectors.

Continued development of the PRAN simulation software should be supported to enhance its application as a design tool for radar reflector networks. Consideration should be given to transporting the software to a portable, generic microcomputer system thus eliminating a hardware dependence on expensive computer and display systems.

The PRAN concept of cross linear polarization requires continued development to obtain the data necessary to further evaluate its potential. This development should involve a static test with the prototype system to re-establish the proof of concept. Furthermore, circular polarization should be tested to determine its potential as a radar discriminant as compared to the cross linear approach. Additional work may include the use of radar tracking algorithms that take advantage of both the vertical and the horizontal return radar signals. Dynamic tests should then be conducted to

evaluate the PRAN as an operational prototype radar positioning system.

The most significant cost reduction in hardware would be the elimination of the requirement for a separate radar to be used only for radar positioning. OSL proposes that a radar scan converter/interface could be used to take advantage of those ships fitted with circular polarized radar. Furthermore, if the PRAN concept is to be utilized, a simpler, more cost-effective antenna and radar system are required.

SOMMAIRE

Le Centre de développement des transports, (CDT), Transports Canada, a confié à la firme Offshore Systems Ltd. (OSL), la tâche d'étudier un système intégré de radionavigation de précision, NAVFIX, dans lequel seraient combinés deux procédés exclusivement canadiens ainsi qu'une technologie française, et d'en réaliser un prototype. L'objectif général fixé à cette recherche a été la réalisation d'un système de radionavigation de précision dans les voies navigables intérieures et dans les eaux littorales. Les objectifs particuliers ont été les suivants:

- a) calcul du point avec une précision à peu près égale ou équivalente à celle des systèmes hyperfréquences actuels;
- b) détermination du point avec un radar embarqué de précision;
- c) utilisation de réflecteurs radar polarimétriques terrestres passifs et une infrastructure naturelle de cibles radar parfaitement reconnues;
- d) intégration des signaux radar à un système d'affichage électronique de cartes de navigation fonctionnant en temps réel, et
- e) livraison à Port-aux-Basques, (Terre-Neuve) d'un prototype répondant aux exigences de Marine Atlantique.

La recherche a commencé par une analyse technique approfondie de deux systèmes de radiolocalisation de cibles radar, à savoir: le système de radionavigation de précision PRAN, étudié par Communications Research Laboratory d'Hamilton (CRL), et le système fabriqué par la société française Virkewin, commercialisé sous le nom de RADARFIX. Ces deux systèmes ont été intégrés au système radionavigation de précision PINS 9000 fabriqué par OSL, qui permet d'enregistrer les signaux de repérage radar et d'en faire l'affichage graphique sur la carte de navigation électronique. Ce dernier système a concurremment enregistré les signaux provenant de divers autres systèmes de radionavigation (Loran-C, Motorola MRS III et Krupp-Atlas Polarfix) aux fins d'établir les degrés de précision relative.

Disponible sur le marché, le système RADARFIX a été le premier à être acheté et analysé; il fait le point en distance et relèvement à partir de cibles radar. Ce système formé de composants standard nécessite une infrastructure de cibles radar très bien définies et parfaitement reconnaissables.

Installé à bord du N.M. OFFSHORE SURVEYOR appartenant à OSL en août 1987, le système RADARFIX a subi des essais dynamiques dans le port de Vancouver. Après plusieurs tentatives, il a été déterminé que ce port ne disposait pas d'un réseau approprié de cibles radar.

Les essais ont donc eu lieu à Steveston Bend sur le fleuve Fraser où se trouvent plusieurs cibles pouvant convenir aux essais du système RADARFIX. La précision de ce dernier a été vérifiée par rapport au système Krupp-Atlas POLARFIX utilisé en parallèle. Les résultats ont montré que la précision statique du RADARFIX a été de 1,77 m avec un écart-type de $\pm 0,98$ m.

Bien qu'encourageants, ces résultats ont amené OSL à conclure que, à moins d'une adaptation le rendant apte à fonctionner n'importe où, ce système ne convenait que partiellement à la radionavigation dans plusieurs voies navigables intérieures et littorales. Afin de relever les performances du système, OSL a étudié la possibilité d'utiliser des réflecteurs polarisants à rainures, ainsi que le procédé de polarisation circulaire. Ce dernier a été choisi parce qu'il accroît le pouvoir de séparation des réflecteurs polarisants par la réjection du clutter terrestre indésirable, et aussi parce qu'il ne requiert, pour fonctionner, qu'une simple adaptation des antennes standard embarquées. De plus, il a été constaté qu'un réflecteur trièdre dont la surface réfléchissante comporte des rainures de section rectangulaire permet de conserver la direction de l'onde incidente en polarisation circulaire, devenant ainsi une cible radar cohérente et parfaitement reconnaissable par le système RADARFIX dûment adapté.

Les essais de ce dernier ont eu lieu en avril 1988 à Deep Cove, anse située dans un tronçon accidenté et très faiblement peuplé du Indian Arm. L'infrastructure de réflecteurs à rainures étant mise en place, le système a été vérifié par rapport au système hyperfréquences de Motorola. Les résultats ont montré que le système RADARFIX dûment adapté permet d'obtenir une précision comparable à celle des systèmes hyperfréquences à condition de disposer d'une infrastructure de réflecteurs appropriée.

L'étape suivante du développement du système RADARFIX adapté a été de modifier le système PINS 9000 pour qu'il puisse accepter une interface utilisateur-machine simplifiée et pour ne plus avoir besoin de l'initialiser à partir d'un point fixe. Pour cela, le fabricant du RADARFIX a dû modifier le progiciel d'exploitation tandis que, pour le PINS 9000, il a fallu que les données de navigation: position (Loran-C), cap et vitesse, soient téléchargées vers le système RADARFIX. Une fois ces modifications accomplies, le système a été essayé avec succès en mode "mains libres" à Deep Cove en mai 1988.

Le système de radionavigation de précision PRAN mis au point par CRL tire parti des travaux faits antérieurement sur le radar polarimétrique et les réflecteurs polarisants. Il est construit autour de trois principaux composants: le réflecteur polarisant, l'antenne à double polarisation et le radar proprement dit. La firme MPB Technologies de Dorval au Québec a reçu en sous-traitance la tâche de réaliser un réflecteur polarisant économique et résistant aux intempéries, construit autour de la grille réalisée par CRL. L'antenne à double polarisation a été mise au point par la firme néerlandaise Christiaan Huygens Laboratorium (CHL) sur les spécifications établies par CRL.

Le système PRAN de CRL intègre sous une même enveloppe des composants de deux systèmes radar distincts ainsi que plusieurs circuits imprimés conçus exprès. Il fait appel à une antenne à double polarisation et à une infrastructure de réflecteurs polarisants passifs pour modifier la polarisation de l'onde incidente d'horizontale à verticale. Des mesures précises de distance et relèvement ont été obtenues pour chaque réflecteur polarisant repéré.

Le système ainsi mis au point a été essayé au banc au CRL, puis expédié à OSL en mai 1988. Il a été par la suite installé sur le N.M. OFFSHORE SURVEYOR, à bord duquel des essais ont été menés en juin de la même année, dans le port de Vancouver. Les essais statiques et dynamiques ont montré que les réflecteurs polarisants peuvent être repérés mais pas séparés du bruit environnant. Le système PRAN a permis d'obtenir des mesures de distance et de relèvement par rapport à plusieurs cibles transitoires.

Le système PRAN a ensuite été essayé à Deep Cove où le bruit environnant est bien moins considérable que dans le port de Vancouver. En mode statique, les réflecteurs polarisants ont été repérés et séparés du bruit environnant. Mais les essais dynamiques ont été moins encourageants, le système ayant fourni des mesures de distance et de relèvement invalides par rapport à plusieurs cibles transitoires.

Les résultats préliminaires d'essais subséquents n'indiquent pas de façon nette que le procédé de polarisation croisée apporte un gain intéressant par rapport à celui de la polarisation circulaire, de moins en ce qui concerne la réjection des bruits parasites. Les essais ont également mis en évidence la nécessité de développer davantage le système PRAN pour en rendre le prototype parfaitement opérationnel. C'est pourquoi aucune recherche supplémentaire n'a été faite sur le problème des réflexions multiples et sur les montages nécessaires au repérage des cibles.

L'autre retombée intéressante du contrat de sous-traitance a été la mise au point du modèle de simulation du système PRAN, destiné à faciliter la sélection des sites d'implantation des réflecteurs, grâce à une représentation numérisée du site géographique et connaissant les caractéristiques dynamiques du navire concerné (en tangage et en roulis), les caractéristiques du système radar utilisé (puissance, fréquence et facteur de répétition d'impulsions), celles du réflecteur (surface équivalente radar et réponse angulaire) et enfin celles de l'antenne (gain, largeur et hauteur de faisceau), autant de paramètres garantissant que les sites choisis se trouvent dans la ligne de visée, qu'ils offrent le moins de réflexions multiples possibles et que la couverture radar assurée est adéquate.

En dernière analyse, c'est le système RADARFIX adapté qui s'est révélé le plus apte des deux à répondre aux exigences de Marine Atlantic pour le site de Port-aux-Basques. C'est ainsi que, en août 1988, ce système a été placé à bord du N.M. ATLANTIC FREIGHTER et que les approches de Port-aux-Basques ont été balisées par un réseau de réflecteurs polarisants. Les premiers essais, menés en septembre et en octobre, ont montré que ce système n'assurait pas la couverture radar escomptée et qu'il ne s'amorçait pas automatiquement durant l'approche de Port-aux-Basques. Mais ces problèmes ont trouvé une solution en novembre 1988 par l'affinement du logiciel et des améliorations apportées au réseau de réflecteurs. Le produit final livré constitue donc le premier système de radionavigation dynamique à réflecteurs, fonctionnant en temps réel.

La recherche à suivre devra porter sur la Voie maritime du Saint-Laurent et sur son balisage à l'aide d'un réseau de réflecteurs, pour résoudre de manière aussi efficace qu'économique le problème de la navigation de précision. A cet égard, OSL suggère que les actions à entreprendre soient dans les domaines suivants:

- a) conception des réflecteurs radar;
- b) conception de logiciels pour la définition du réseau de réflecteurs;
- c) choix entre les procédés de polarisation croisée ou circulaire;
- d) matériel informatique embarqué de type simplifié.

Chacune de ces idées fait l'objet d'une explication dans le paragraphe suivant.

Deux modèles inédits de réflecteurs radar ont été utilisés aux fins de la recherche sur le système NAVFIX: un à surface réfléchissante rainurée et un à grille polarimétrique. Tous les deux ont bien fonctionné tant en polarisation circulaire (RADARFIX adapté) qu'en polarisation croisée (PRAN). Ces deux procédés devront être approfondis sous l'angle des performances (surface équivalente radar et réponse angulaire) en fonction du coût de fabrication. L'attention devra également porter sur les techniques de mise en place des réflecteurs, soit individuels, soit groupés.

La mise au point du logiciel de simulation du système PRAN devra être poursuivie dans le but d'en faire un outil approprié pour la définition des réseaux de réflecteurs. Notamment sous l'angle de son adaptation à un micro-ordinateur, de manière à ne pas devoir faire appel à un matériel coûteux de traitement et d'affichage des données.

Le procédé de polarisation croisée, à la base du système PRAN devra être approfondi de manière à en tirer tout le parti possible. Il faudra prévoir des essais statiques mettant en oeuvre le prototype pour en revalider le principe. De plus, le procédé de polarisation circulaire devra être également approfondi pour en vérifier l'aptitude à la discrimination des ondes radar, comparativement à la polarisation croisée. D'autres recherches pourront être consacrées aux algorithmes de poursuite radar tirant parti des deux polarisations verticale et horizontale. Enfin, des essais dynamiques devront être menés aux fins d'évaluer le prototype PRAN et établir sa fonctionnalité comme système de radionavigation au radar.

La meilleure façon de réduire le coût du matériel serait de ne plus avoir besoin d'un radar séparé servant uniquement au repérage radar. A cet égard, OSL est d'avis qu'un convertisseur ou une interface de balayage pourra servir dans le cas d'un navire équipé d'un radar à polarisation circulaire. De même, si on désire tirer parti du système PRAN, il y aura lieu d'utiliser un ensemble antenne-système radar à la fois plus simple et plus économique.

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GLOSSARY OF ABBREVIATION, ACRONYMS, AND SYMBOLS

ACCI	-	Associated Controls & Communications, Inc.
ASCII	-	American Standard Code for Information Interchange
ASF	-	Additional Secondary Factor
CCG	-	Canadian Coast Guard
CHL	-	Christiaan Huygenslaboratorium
CHS	-	Canadian Hydrographic Service
CRL	-	Communications Research Laboratory
dB	-	Decibels
DMA	-	Dominion Marine Association
DSS	-	Department of Supply and Services
ENC	-	Electronic Navigation Chart
ERM	-	Ecart Relatif Moyen
FAT	-	Factory Acceptance Test
GPIO	-	General Purpose Input Output
IF	-	Intermediate Frequency
MA	-	Marine Atlantic
MPBT	-	MPB Technologies, Inc.
NAVFIX	-	Precise Radar Integrated Navigation System
OSL	-	Offshore Systems Ltd.
PAB	-	Port Aux Basques, Newfoundland
PINS	-	Precise Integrated Navigation System
PNS	-	Precise Navigation System
PPI	-	Plan Position Indicator
PRAN	-	Polarimetric Radar for Accurate Navigation
PRANS	-	Precise Radar Aids to Navigation System
RBTI	-	Radar Based Technologies Inc.
RF	-	Radio Frequency
SINADS	-	Shipboard Integrated Navigation And Display System
TDC	-	Transportation Development Centre of Transport Canada
UBC	-	University of British Columbia
UP	-	Unsolicited Proposal
UPP	-	Unsolicited Proposals Program

1.0 INTRODUCTION

1.1 Project Overview

A one day workshop on precise navigation systems co-sponsored by the Transportation Development Centre (TDC) of Transport Canada and the Dominion Marine Association (DMA) was held in Ottawa in November, 1986 [1]. The Workshop reviewed the results of research and development activities relating to precise navigation sponsored by TDC. At the meeting, Offshore Systems Ltd. (OSL) presented the Precise Integrated Navigation System (PINS 9000) as an electronic navigation chart display system suitable for coastal and inshore navigation. Also reviewed at the meeting was the Polarimetric Radar for Accurate Navigation (PRAN) by Communications Research Laboratory (CRL) as a viable alternative to microwave systems currently in use. The PRAN system proposed the utilization of a network of passive polarimetric twist reflectors in place of the microwave transponders used in active systems. This passive system would eliminate the need for power and maintenance for base stations thus increasing reliability and reducing costs. A second radar positioning concept called RADARFIX developed by Virkewin of France was also presented by OSL. The RADARFIX system utilizes localized radar signal digitizing and radar image processing by computer to obtain range and bearing data to conspicuous radar targets. The data are then used to calculate a position.

The support for these new radar positioning concepts by the Canadian Coast Guard (CCG) and the DMA prompted OSL to submit an Unsolicited Proposal (UP) to the Department of Supply and Services (DSS) on December 15, 1986. The UP was reviewed and accepted in principle at a DSS Interdepartmental Committee Meeting held on January 23, 1987, with financial support being provided by DSS, Marine Atlantic (MA), and TDC. The final contract was awarded on June 11, 1987.

The principal objective of the project was to develop, demonstrate and evaluate a prototype precise radar integrated navigation system for coastal and inshore waterways. The process involved the continued development of PRAN by CRL and the incorporation of RADARFIX and PINS into a prototype radar positioning system called NAVFIX.

1.2 Background

In 1977 the Dominion Marine Association (DMA), which is an organization made up of shipping companies operating in the St. Lawrence Seaway, the St. Lawrence River and the Great Lakes, in conjunction with Associated Controls and Communications Inc. (ACCI) in Massachusetts, evaluated a

Precise Radar Aids to Navigation System (PRANS) [2]. The PRANS was to provide assistance in docking manoeuvres and allow automatic navigation to within three metres of a predetermined course. The system consisted of a shipboard radar interfaced to a minicomputer. Range measurements to a network of passive retro-reflectors in known locations were used to determine the ship's position relative to a desired course. Continuous navigation was to be realized by automatically switching between successive sets of standard retro-reflectors stationed along the waterway.

In September 1978 the DMA tested the ACCI system on a stretch of the St. Lawrence Seaway near Prescott, Ontario. Trials conducted during the summer and fall of 1980 indicated that although PRANS showed promise, a number of problems needed to be resolved before the system could be declared operational. A particular problem was that although PRANS performed satisfactorily in static tests it tended to be unreliable during dynamic tests due to a frequent loss of signal. Failure to acquire targets, maintain adequate signal strength and inconsistencies in equipment performance were attributed to radar clutter and to multipath fading. The radar clutter and multipath fading problem was improved by using larger retro-reflectors and constellations of retro-reflectors, both serving to increase the effective radar cross section and introduce space diversity. The problems of retro-reflector acquisition and tracking was deemed fundamental to the successful operation of the concept.

In a study conducted at Communications Research Lab (CRL), McMaster University in Hamilton in 1983, it was found that the use of cross linear polarization and space diversity provided a solution to many of the shortcomings of the ACCI PRANS [3]. Subsequent to that study a trihedral reflector, equipped with a twist grid to rotate the polarization of the incident radiation, was the subject of a Canadian patent application [4]. Further study in the area of passive polarimetric reflectors for precise radar navigation led to the development of an experimental system called Polarimetric Radar for Accurate Navigation (PRAN) [5],[6].

The PRAN system relies on cross linear polarization as the radar discriminant. PRAN uses a dual-polarized antenna and a network of the passive polarimetric twist reflectors to convert the incident radar wave from horizontal to vertical. Accurate range and bearing data are determined for each twist reflector detected in the network. The twist reflectors can be detected in spite of the presence of strong radar clutter arising from unwanted reflections from fixed objects in the vicinity.

2.0 RADARFIX

2.1 Background

Radar Based Technologies, Inc. (RBTI) of Del Mar, California and Virkewin of Roggenhouse, France are the co-developers of the RADARFIX system. RBTI and Virkewin have invested eight years of research and development into precise radar positioning [7].

RADARFIX is a radar positioning system that utilizes conspicuous, natural radar targets. The onboard computer analyzes the radar signals and processes certain echoes that are uniquely identifiable. Based upon the range and bearing to those echoes, whose position coordinates have been previously recorded, the system can deduce the vessel's position.

A good radar target is one which sends back a strong, localized echo that is isolated from all neighbouring echoes. Furthermore, the position, height and size of the target must be precisely known. Typical targets utilised are aids to navigation (buoys, dolphins and lights) and precise coordinates can be obtained through government agencies such as the Canadian Hydrographic Service (CHS).

The radar utilized in the RADARFIX system is a standard off-the-shelf Swiss Radar (Model JFS 32R) from JFS-Electronic in Rotkreuz, Switzerland. The solid state modulator-receiver and antenna motor are directly coupled with the antenna and mast-mounted thus no waveguide is required. A special radar cable runs between the antenna and the plan position indicator (PPI) display unit. A low noise video amplifier provides excellent display resolution and superb target separation. The published range discrimination of the radar is 8 metres.

The manufacturer's start-up procedure requires that a human operator identify a known radar target on the PPI by entering the range and bearing from the vessel to the radar target, the RADARFIX system will then "lock-on" to the radar target. After a second radar target has been acquired in a similar manner the RADARFIX is operational. This manual procedure can be automated if the vessel is stationary and RADARFIX is given an initial position and heading.

Once the initial heading from the ship's gyrocompass has been entered, the RADARFIX maintains its orientation by monitoring the output of a rate gyro. Real-time heading data are required to track the network of radar targets. During operation, the RADARFIX system provides precise range and bearing data to a Kalman filter which in turn generates an

accurate state vector reflecting the ship's present heading and position.

As delivered from the factory, the Swiss Radar has only a PPI display for displaying target echoes. The radar targets that RADARFIX "locks on" and tracks have a range and bearing window immediately behind the echo on the PPI display. The window indicates which radar targets are being used in the position calculation. The discrepancies between the expected and measured ranges and bearings to the radar targets are calculated and displayed on a separate ASCII terminal. Also displayed are signal strength values for each of the radar targets. Good radar targets have low range and bearing discrepancies and a high signal strength value. These values provide the observer with an indication of system performance.

The internal precision monitoring within RADARFIX is called Ecart Relatif Moyen (ERM) or Mean Relative Difference. ERM is a combination of the range differences and the bearing differences as determined from the expected range and bearing to the radar targets and the measured range and bearing. The measured minus the expected range and bearing differences are divided by a typical range and angle difference respectfully. These standardized values are then averaged with previous readings. The now unitless relative differences can be added and averaged again to yield the ERM value. Typically, differences are 0.1 degree of angle and 1.8 metres of range. A good ERM value would be close to one.

Virkewin claimed that RADARFIX could provide a position to better than 1 metre using a standard shipboard radar. Radar range resolution is dependant upon the ability to detect the leading edge of the returned pulse from the radar echoes [8]. The return pulse is typically non-uniformly shaped thus discrimination is limited to one-half of the pulse length. Given a pulse length of 0.05 microseconds (or 15 metres at the speed of light) then the best possible range resolution is only 7.5 metres. Furthermore, with a typical marine radar antenna horizontal beamwidth of 1 degree, a bearing resolution of only 0.5 degrees can be achieved. At 1000 metres, this equates to 8.7 metres of error.

However, Virkewin stated that advances in the theory and technology of radar signal digitizing and radar image processing by computer have made position accuracies of 1 metre possible. The proof of this claim is provided in Section 2.3 (Subsystem Evaluation) that compares the RADARFIX system to several proven positioning systems.

Another feature of the RADARFIX system is Automatic Landmark management. This feature relieves the operator from choosing which radar target to track. The process involves setting up a table of radar targets which are defined by their specific

interval of detectability along the vessel's course. The system will utilize only the radar targets within the area of operation and ignore all other radar targets.

2.2 Subsystem Modifications

During the evaluation of RADARFIX (Refer to Section 2.3) two major deficiencies were identified:

- a) the system was not capable of starting up without human interaction; and,
- b) the system was not able to work satisfactorily in all areas.

The modifications to RADARFIX to correct these deficiencies are discussed in the following paragraphs.

The RADARFIX system was designed to utilize an ASCII terminal to start-up the system at a fixed, known point. The radar target data or the vessel's heading and position are entered manually via the terminal. There is no external computer control and no provision to start-up dynamically.

One of the principal objectives of the radar positioning system development was to provide a system comparable in positional accuracy to microwave systems. However, this also inferred by default that the system be simple to operate. To this end, OSL:

- a) developed software to emulate and replace the ASCII terminal; and,
- b) directed the RADARFIX manufacturer to incorporate a dynamic start-up routine.

These changes allowed the user to enter the vessel speed along with the initial heading and position to dynamically start-up the RADARFIX system. Furthermore, the ASCII terminal emulation software allowed the PINS 9000 system to download the speed, heading, and position data as derived from Loran-C to the RADARFIX system. RADARFIX would then use the data to start a Kalman filter tracker algorithm until it "locked-on" to its radar targets.

The other major deficiency that required modification to the Swiss Radar was that RADARFIX did not work at any location. Specifically, a suitable network of conspicuous radar targets was not found for Vancouver Harbour (Refer to Section 2.3). To increase the versatility of RADARFIX two concepts were investigated:

- a) circular polarization; and,
- b) radar reflectors.

Virkewin claimed that the standard radar retro-reflector can be used to increase the signal strength from a specific radar target. It was found that RADARFIX targets augmented with standard radar retro-reflectors showed increased signal strength and decreased range and bearing differences. The results indicated that standard radar reflectors could improve the reliability and performance of the RADARFIX system.

Offshore Systems Ltd. then proceeded, in conjunction with the Department of Electrical Engineering at the University of British Columbia (UBC), to develop a circular polarizing grid for the Swiss radar antenna and corrugated radar twist reflectors for the RADARFIX system. Circular polarization was chosen since it both enhanced the ability to uniquely discriminate twist reflectors from the background by suppressing the unwanted land clutter and that polarization conversion could be accomplished by a simple modification to the existing standard marine radar antenna [9]. Furthermore, a trihedral radar reflector with a corrugated reflection surface of rectangular grooves was found to maintain the sense of the incident circular polarized radar wave and thus provided a coherent, conspicuous radar target for the modified RADARFIX system [10].

The phenomenon of circular polarization is well known [11]. Indeed, some commercially available radar systems have an optional circular polarization mode in addition to the standard horizontal polarization mode. This circular polarization mode is used in adverse weather conditions, typically rain and snow, to suppress the radar clutter from the precipitation. Rain and snow are reflectors that are spherical and symmetrical. The detection of desired radar imagery, when using circular polarization, is mainly due to the fact that a lot of echoes are asymmetrical, although the signal level is generally reduced when compared with like linear polarization.

Circular polarization has the unique feature of not being able to detect its own echo since a symmetrical reflector will return a circularly polarised signal rotating in the opposite sense to the outgoing signal. That is an outgoing right hand rotation will reflect as a left hand rotation.

There are many targets that can be used for radar navigation [12]. A dihedral, a two-sided corner reflector, returns an echo of the same sense as the outgoing polarization. Dihedral reflectors are referred to as "double bounce" or "even bounce", which simply means that the outgoing rotation of the circular polarization is reversed twice as it bounces off the two sides of the dihedral and the antenna transmitting the signal can therefore detect the echo.

A conventional trihedral or three-sided corner reflector returns an echo of the opposite sense to the outgoing polarization when using a circularly polarised antenna. This is referred to as an "odd bounce" reflector and behaves the same way as a single bounce symmetrical reflector, resulting in a total loss of signal. However, the corrugated radar twist reflector is a trihedral radar reflector with a corrugated reflection surface of rectangular grooves on one face. The corrugated radar twist reflector maintains the sense of the incident circular polarization and thus provides a coherent radar target.

To further investigate the modified RADARFIX system, OSL made minor modifications to the Swiss Radar to permit the display of the return video signal on an oscilloscope. The display provided a means to directly compare the relative signal strength of target echoes and thus assist in the analysis of multipath fading. Unfortunately, due to the nature of the radar receiver it was difficult to interpret the vertical scale of the display. Further modifications and/or calibration would be required to convert the Swiss Radar to an instrumentation radar for accurate signal strength and/or radar cross section measurements.

OSL also modified the Swiss Radar sensitivity time control (STC) circuitry to allow for user control of the STC level and slope. Ideally, the STC curve could then be matched to the return radar signal to uniformly suppress the unwanted background clutter over the entire spectrum. Trials were conducted with different STC settings in an attempt to maximize the corrugated radar twist reflector signal strength while minimizing the unwanted background clutter. The results indicated that with careful radar gain and STC settings the corrugated radar twist reflectors could be completely isolated from the background clutter under ideal conditions.

2.3 Subsystem Evaluation

Offshore Systems Ltd. received the RADARFIX system in Vancouver during August 1987 and mobilized the system on the M.V. "OFFSHORE SURVEYOR" for dynamic trials. A systems analyst from Virkewin provided training and ensured the RADARFIX system was properly installed. The first area of operation was Vancouver Harbour near the Second Narrows Bridge. After several weeks of investigation results indicated that a suitable network of conspicuous radar targets could not be found.

The next phase of testing required a better radar target area. This new area was the Steveston Bend on the Fraser River. At this location there were many strong, localized echoes from navigation lights and dolphins. RADARFIX worked

well in this environment so it was decided to compare the system to another precise positioning system.

The Krupp-Atlas Polarfix was used for the evaluation and was provided by the Department of Public Works Canada (Fraser River Survey) - Steveston office. The Polarfix system is a laser-based range and bearing system with automatic tracking capabilities. The published accuracy of the Polarfix system is ± 0.1 metres.

Both the RADARFIX and the Polarfix systems were interfaced to the OSL PINS 9000. All positioning data were recorded for post processing. The results from the Polarfix - RADARFIX trials indicated that in a static mode the vector of disclosure between the two systems was 1.77 metres with a standard deviation of ± 0.98 metres. The RADARFIX system also tracked reasonably well throughout the network and compared favourably (± 5 metres) with the Polarfix system.

The results from Steveston Bend were very encouraging but OSL concluded that unless RADARFIX could be made to work at any location then it had limited practical use for many coastal and inland waterways. Another limitation was that RADARFIX could not be started automatically, without human interaction. To overcome these deficiencies OSL implemented modifications to the RADARFIX system (Refer to Section 2.2). The modified RADARFIX system utilized a circular polarized radar antenna and a network of corrugated radar twist reflectors to provide coherent, conspicuous radar targets. Software modifications allowed for dynamic start-up and remote computer control which eliminated the need for manual operation.

The next phase of the evaluation was to deploy the modified RADARFIX system in Deep Cove near North Vancouver. Deep Cove is a rugged, sparsely populated section of Indian Arm. The standard marine radar display of Deep Cove is shown in Figure 1. A network of corrugated radar twist reflectors was established (Figure 2) and the performance of the system was verified against a Motorola microwave positioning system.

Initial trials indicated that due to multipath fading the corrugated radar twist reflectors could not be consistently tracked. To minimize signal fading, a second reflector was established vertically above the existing reflectors. The vertical separation was fixed at 1.5 metres. Subsequent trials found that the double reflectors with space diversity significantly improved the RADARFIX performance. The system was able to provide good positioning throughout the area of coverage. The modified RADARFIX display (Figure 3) clearly shows the twist reflector echoes with the computer generated flags to mark the landmarks.

The modified RADARFIX system was compared to a Motorola Mini-Ranger III microwave positioning system by recording simultaneous position data with the PINS 9000 system. The results indicated that the difference between the Motorola position and the RADARFIX position was better than + 3 metres over the area of coverage. The RADARFIX indicated a static ERM value of less than one (typically 0.5) and dynamically the ERM was typically less than three. These values, according to the manufacturer, indicate that the system was performing extremely well.

Finally, the "hands-free" mode was tested with the PINS 9000 downloading the vessel's speed, gyrocompass heading and Loran-C position to the modified RADARFIX system. It was found that the Loran-C position had to be offset to account for the land transmission-path effect also known as the additional secondary factor (ASF). The offset was determined by comparing the Loran-C derived position to the Motorola MRS III microwave position. Utilizing the calibrated Loran-C position, the modified RADARFIX system was consistently able to start-up automatically.

3.0 PRAN DEVELOPMENT

3.1 Background

The St. Lawrence Seaway system provides the means of transporting over half of Canada's commercial goods and exports by a 3,200 km inland waterway which services the industrialized heartland of North America. Regrettably, this two-way traffic flow rate is often severely reduced by inclement weather and darkness. It has been estimated by the Dominion Marine Association, that a minimum of six percent of the seaway capacity, representing millions of dollars, is lost annually due to idle ship time. Consequently, any cost-effective method that would increase the throughput capacity of this waterway would be of significant interest to the various shipping companies and the seaway authority.

The Dominion Marine Association under contract to the Transport Development Centre, arranged a series of trials of a Precise Radar Aids to Navigation System (PRANS) developed by Associated Controls and Communications Inc. of Salem, Massachusetts in the Cornwall area of the Seaway between 1978 and 1980. By radar ranging to a series of reflectors at known locations, a minicomputer in the trials ship attempted to calculate the ship's position relative to the desired course.

Although the PRANS concept showed promise, the results of the trials were less than satisfactory. This system proved to be unreliable during dynamic testing, because of the frequent loss of signal. Spurious signal clutter and fading, due to multipath propagation, were the two major factors that caused the system to be unreliable.

From 1982 to the present, the Communications Research Laboratory (CRL) at McMaster University has been under contract to address the major problems that were identified in the PRANS trials. CRL analyzed the problems and pursued the strategy of artificially changing the polarized radar signal to simplify the discrimination between the passive reflectors and the ambient ground clutter. This co-operative reflector technique produced a significant gain in the signal-to-clutter ratio. CRL has successfully demonstrated under static conditions, that passive reflectors of their design will rotate the polarized radar signal by 90 degrees. Consequently, by utilizing a like polarized receiving antenna, these specific reflectors can be readily discriminated from the surrounding ground clutter. In a similar fashion, CRL has successfully demonstrated that by applying space diversity techniques (vertically separated reflectors), the multipath propagation problems that plagued the PRANS trials can be readily eliminated.

Since the two major problems identified in the earlier PRANS trials were rectified, the next step was to dynamically test the polarimetric radar concept for accurate navigation. A one-day workshop on precise navigation systems co-sponsored by the Transportation Development Centre (TDC) and the Dominion Marine Association (DMA) was held in Ottawa in November 1986. It was concluded that CRL, working in conjunction with OSL, would continue development on its Polarimetric Radar for Accurate Navigation (PRAN) system.

3.2 Objectives

The primary objectives of the PRAN subsystem development were:

- a. modify the PRAN system to determine accurate range and bearing data;
- b. provide an output interface for the range and bearing data;
- c. provide design specifications for the trihedral twist reflectors and dual-polarized antenna;
- d. conduct static and dynamic evaluations;
- e. develop simulation software to solve the problem of multipath;
- f. deliver and install a working system to Marine Atlantic for the M.V. 'ATLANTIC FREIGHTER'.

3.3 Subsystem Modifications

The original PRAN system consisted of two Decca marine radar units connected to a dual-polarized parabolic antenna. The antenna beam pattern was only 1.5 degrees in azimuth and elevation and thus was suitable only for testing purposes. One radar unit was used to transmit and receive the like-polarized signal. The second radar was used exclusively to receive the cross-polarized echo. Consequently, most of the circuitry in the second radar system was redundant.

The objective of the PRAN development was to produce an operational prototype shipboard precise radar positioning system (Refer to Appendix A). To this end, a more compact system was developed by retaining from the second radar only those components required to receive the RF energy and extract the video signal.

The IF signal in the radar is the result of combining in the mixer the signal frequency produced by the magnetron and the frequency from the local oscillator. Since the PRAN system has only one signal source, the magnetron, and two receiver sections (horizontal and vertical), the same local oscillator was used to ensure the IF signals from both polarizations were at the same frequency. To accomplish this, a hybrid tee was connected to the local oscillator to split the signal between the two receivers.

To measure range to a target, the radar must be able to accurately determine the travel time for the radar signal at some reference point along the signal path between the magnetron and the antenna feed. The radar electronics are subject to a small amount of jitter that can degrade the timing resolution. It was thus decided to fix the reference point inside the transceiver unit by using a cross-guide directional coupler. This coupler was inserted after the magnetron to detect the outgoing RF pulse.

On detection of the outgoing pulse, the zero range mark is set which then enables the range counter. The range counter is a 50 MHz (20 nanoseconds) system which corresponds to a range resolution of three metres. The return video signal and a user-controlled adaptive threshold value are compared by a video comparator to determine if a target is present. If the video signal level exceeds the threshold level, then the range and bearing are latched. The value stored in the range counter latches represents the number of clock pulses that have occurred between the zero range mark and when the target threshold was detected. The range is output as a 15-bit data word (0 - 32767).

The bearing is determined by decoding the data from the optical shaft encoder. The shaft encoder is located in the base of the dual-polarized antenna and provides an

incremental output. The bearing is output as a 12-bit azimuth value (0 - 4095). The range and bearing data are then transfer via a GPIO interface out to the PINS 9000 computer. Both the range and the bearing are converted into metres and degrees respectfully by the PINS 9000 computer.

The adaptive threshold circuitry divides the range, 0 to 11640 metres, into 32 steps. The first step is 480 metres and the next 31 steps are increments of 360 metres. The threshold values form a step function that decreases as one over the range to the fourth power. This approach, very approximately, removes the range dependence of the return RF signal. Depending on the range of the sample video signal being tested, the threshold value is changed accordingly.

3.4 Simulation Software

To establish a network of radar reflectors there are several requirements and constraints to be considered. Primarily, they must provide adequate coverage over the entire area of operations. This implies that at least two, preferably four, reflectors are visible at all times. Other parameters are geometry, line of sight, land use, and multipath. It is extremely difficult, if not impossible, to establish a network of reflectors that satisfied each requirement in an optimal manner.

The PRAN simulation was designed to assist in the selection of reflector sites. The first task is to assimilate all the known factors. These factors include a digital terrain model of the area, vessel dynamics (pitch and roll), radar characteristics (power, frequency, pulse repetition factor), reflector characteristics (radar cross section, angular response), and antenna specifications (gain, beamwidth, height). These parameters can then be utilized to ensure reflector sites have line-of-sight, minimal multipath fading and adequate coverage.

Once the reflector network has been designed and the vessel route selected then the next phase of the simulation can calculate the predicted position error along the route. The program accounts for the ship's motion, reflector geometry and the various radar and terrain parameters using a Least Squares solution. Also generated is a list of reflector sites visible to the vessel along each section of its route. Detection of reflectors is based on the ship-reflector aspect angle, multipath and the modified antenna beam pattern caused by vessel pitch and roll. The ship-reflector aspect angle is used to vary the reflector radar cross section. The results of the simulation indicated that the PRAN system utilizing a seven station twist reflector network in Port Aux Basques would achieve position accuracy ranging from 5 to 8 metres

along the route with a mean position error of approximately 7 metres (Refer to Appendix A).

3.5 Twist Reflectors

The design, construction and testing of the twist reflectors were subcontracted to MPB Technologies Inc. (MPBT) of Dorval, Quebec (Refer to Appendix B). The twist reflector specifications were provided by CRL and based upon previous reflector investigations.

The original CRL twist reflector design consisted of a set of parallel wires mounted on one face of the trihedral. The enamelled copper wires were 0.05 mm diameter and suspended 19 mm above one face of the trihedral by mounting the wires on rigid bristol board and styrofoam. A plastic film radome protected the wire grid and supporting dielectric from the elements. Although these prototype reflectors work well, it was concluded that they were not suitable for permanent field installation. Furthermore, they were difficult to assemble and would require a more robust radome to protect the wire transmission grid.

The technique MPBT chose to construct the wire grid was a silk screening process which lay down silver epoxy traces on a mylar substrate. Unfortunately, due to a limitation in the silk screen process, the smallest possible width for the traces was 0.1 mm. Therefore, it was necessary to experiment with the wire spacing and the height off the reflector surface to optimize the design.

Two different silver epoxy trace widths with a range of spacings were investigated. The first trace width was 0.1 mm and the wire spacing ranged from 6.5 mm to 9.5 mm in 0.5 mm increments. The second trace width was 0.2 mm and the wire spacing ranged from 8.5 mm to 11.5 mm in 0.5 mm increments. Each grid was tested using different spacing off the reflector surface. The testing was initially conducted at MPBT then transferred to CRL to ensure testing procedures matched the previous work done by CRL on the prototype twist reflectors. The results indicated that the best mylar grid had a trace width of 0.1 mm, wire spacing of 6.5 mm and a separation off the reflector surface of 17 mm.

The mylar grid twist reflectors did not convert the radar signal from horizontal to vertical as efficiently as the original wire grid twist reflectors. The conversion efficiency was down by as much as 5 dB. However, the larger size and precise orthogonal construction of the MPBT twist reflector produced a larger vertical signal and it is the vertical signal level that triggers the adaptive threshold circuitry in the PRAN system.

The final completed version of the MPBT twist reflector utilized the new mylar grids as determined by CRL. The grid was adhered to the surface of a precisely skived (17 mm) styrofoam sheet which was then attached to the trihedral reflectors. The precision trihedral was constructed of anodized aluminium and bolted together to form near perfect orthogonal sides. The approximate corner length for each side of the twist reflector is 70 cm which gives a theoretical radar cross section of 890 square metres. The trihedral was then placed into a fibreglass protective shell and the open face was covered with a polyethylene (Ethafoam) radome. The radome protected the mylar grid from the weather and reduce the surface area of the reflector to minimize wind loading.

Concurrent with the MPBT twist reflector development, OSL developed, in conjunction with UBC, the corrugated radar reflector. The mylar grid and foam dielectric of the MPBT design is replaced with a corrugated reflection surface of rectangular grooves. The groove spacing, depth and thickness are determined from the radar wavelength.

It was found experimental at UBC test facilities that the corrugated reflector has a slightly wider response angle than the MPBT twist reflectors for both cross linear and circular polarization. It was also found that the MPBT twist reflectors worked with circular polarization similar to the corrugated twist reflectors. Similarly, the corrugated twist reflectors worked with cross linear polarization. Further study found that for circular polarization the corrugated reflection surface and the transmission grid did not have to be precisely oriented to the incident radar wave as required for cross linear polarization. Thus, when using circular polarization, the twist reflector mounting was a simpler task.

Another advantage of the corrugated reflector is that there is no requirement for a foam dielectric to support the wire grid. The dielectric can deteriorate when subjected to the marine environment and thus lose its low loss propagation characteristics. Using corrugated reflection surfaces may also lead to reduced fabrication costs and the elimination of a radome for most applications. A radome would still be desirable where the reflector is subjected to high winds.

3.6 Dual-Polarized Antenna

The prototype PRAN system utilized a 1.2 metre parabolic dish antenna that produced a pencil beam with a 3 dB beamwidth of 1.5 degrees in azimuth and elevation. This antenna was suitable for investigation into polarization as a radar discriminant but was not suitable for marine applications.

Several antenna manufacturers were contacted in an effort to best determine the most appropriate antenna configuration with due regard for cost, performance and technical risk. One major concern identified from the start was that the dual rotary joint had to be an integral part of the antenna system. The previous PRAN antenna system was water damaged due to difficulties mating the rotary joint to the antenna. The antenna manufacturer which could provide the complete solution, therefore providing the least technical risk, was the preferred choice.

Christiaan Huygenslaboratorium (CHL) was the chosen dual-polarized antenna manufacturer. CHL had previous experience with dual-polarization and the construction of slotted waveguide antennas. The proposed antenna system also included the dual rotary joint integrated into a rugged marine housing. The antenna system provided antenna azimuth information by a optical incremental hollow shaft encoder. The complete system weighed 130 kilograms and required 220/460 V power supply for the drive motor.

A Factory Acceptance Test (FAT) was performed in April 1988 (Refer to Appendix C). According to the FAT, the antenna performance exceeded all design parameters except for the vertical beam pattern. The vertical beam pattern design specification called for 20 degrees or better and the final antenna system provided 18.4 degrees. This was not considered significant by CRL and therefore the FAT was accepted. The horizontal beamwidth of the dual-polarized antenna was 0.92 degrees with an antenna gain of 32.7 dB and a cross-polarization rejection greater than 30 dB. The antenna rotation rate was 24 revolution per minute and the incremental optical hollow shaft encoder output 4096 pulses per revolution to provide relative bearing information.

3.7 Subsystem Evaluation

The CHL antenna was received in April 1988 and installed on the OSL M.V. 'OFFSHORE SURVEYOR' for testing with the CRL PRAN system. An antenna pedestal was mounted on the deckhead of the wheelhouse. The 15 cm support pipe also penetrated the deckhead to allow waveguide and communication cable to run between the PRAN system and the CHL dual-polarized antenna. The PRAN system was bench tested at CRL and then shipped to OSL in May 1988. The main PRAN unit was located on the deck in the wheelhouse directly beneath the CHL antenna. Two runs of rigid WR-90 waveguide with a 30 cm flexible waveguide section were used to couple both the horizontal and vertical antenna feeds to the PRAN unit. The cable carrying the bearing information from the optical shaft encoder was also passed down through the pedestal and connected to the PRAN unit. To complete the onboard installation; the PPI, transceiver and rectifiers were

connected together and tested to confirm functionality. The range and bearing output from the PRAN system was passed to the PINS 9000 via a 50 conductor GPIO cable.

The prototype PRAN system proved the concept of cross linear polarization as a radar discriminant [6]. Static tests indicated that twist reflectors could be isolated on the PPI display. The first logical test at Vancouver of the NAVFIX development system was to reconstruct the static test to verify the system was performing as expected.

The mobilized PRAN system on the M.V. "OFFSHORE SURVEYOR" was docked at Lynnwood Marina just west of the Second Narrows Bridge. Two MPBT twist reflectors were mounted on a support stand and placed approximately 750 metres across the harbour. Second Narrows Bridge, a large steel crossing, ran parallel to the test range and was within 100 metres of the reflector site. The reflector site was also located only 50 metres away from several concrete grain elevators. The reflectors were placed as close as possible to the foreshore and aimed directly at the antenna platform.

The static tests attempted to isolate the twist reflectors on the PPI display. The video gain control was adjusted to eliminate as much of the background clutter as possible yet maintain the signal from the twist reflectors. The testing took place over several days. The results indicated that the signal from the reflectors fluctuated greatly over different time periods. The fluctuation was attributed to multipath and was most likely due to the tidal variation which can be as much as 4 to 5 metres. Regardless of the multipath, the reflectors could not be entirely isolated next to the bridge and grain terminal. This result was expected since the bridge had many trihedral and dihedral reflectors formed by the steel girders.

Dynamic tests were then conducted in Vancouver Harbour. A pair of reflectors were established and the vessel sailed throughout the area of coverage to determine if the reflectors could be isolated. Results showed several spurious radar returns throughout the harbour and the reflectors could not be uniquely identified or isolated.

The next phase of testing took place in Deep Cove near Vancouver. The Deep Cove radar environment is significantly less hostile than Vancouver Harbour but it does typify the rugged, treed coastline of the Pacific Northwest. Four reflector sites were established with two of the sites on small islands. The island sites had single corrugated type reflectors, another site had a single MPBT twist reflector and the last site had one corrugated reflector co-located with an MPBT twist reflector. A three metre space diversity was utilized at the last site to minimize the signal fading due to multipath.

Under static conditions, with the gain adjusted to minimize the unwanted background clutter, it was possible to isolate the reflectors. The reflector site that utilized space diversity was consistently detectable whereas the other sites were subject to the effects of multipath. The MPBT twist reflector site had the most inconsistent signal but this was expected since it has a smaller radar cross section and angular response than the larger corrugated reflectors. The MPBT twist reflector did, however, perform quite well and was clearly detectable with the PRAN system.

Various vessel manoeuvres were conducted to observe the effects of multipath on the detection of the reflectors. These dynamic trials were less encouraging with the PRAN system outputting invalid range and bearing data to several spurious targets.

Several deficiencies were noted during the evaluation of the PRAN system. The system was cumbersome and difficult to operate. The PPI display did not match the range and bearing data being output to the PINS 9000. Furthermore, the PPI display and the GPIO data output could not be run simultaneously which made analysis of the adaptive threshold circuit difficult. The trials clearly indicated that further PRAN development is necessary to make the system a fully operational prototype radar positioning system. Thus, further tests with the PRAN system were not undertaken.

4.0 PINS DEVELOPMENT

4.1 Background

Offshore Systems Ltd. (OSL) has a long history of electronic navigation chart (ENC) systems development. OSL, through its associate service company Offshore Survey and Positioning Services Ltd. (OSPS), has been providing ship navigation and oil rig positioning technology since 1977. In 1979, OSPS developed a Precise Navigation System (PNS) to accurately navigate ships in and out of the narrowly dredged channels of Tuktoyaktuk and McKinley Bay in the Beaufort Sea.

PNS used a number of short-range microwave transponders positioned ashore to precisely range to a shipboard receiver. Position data from two to four transponders was displayed on a monochromatic video monitor using a split screen presentation of both small and large scale charts. The calculations, positional smoothing, and chart shoreline graphics were processed by a Hewlett Packard HP9825 desktop

calculator. This first generation electronic chart system was very successful in the Beaufort Sea.

A second iteration PNS system was developed in 1982. This system utilized colour filled charts instead of the monochrome shore outline of the original system. In addition to the colour charts, this advanced PNS system featured survey grids and a much more powerful HP9826 computer.

In 1984, OSL commenced development of a second-generation electronic chart system or Precise Integrated Navigation System (PINS 9000). Based on our PNS experience, the following three requirements were considered essential for an advanced electronic navigation chart display system:

- a) accurate colour filled charts;
- b) precise vessel positioning; and,
- c) a user-friendly interactive keyboard.

These features are discussed in the following paragraphs.

Accurate hydrographic chart digitizing, which can easily address various chart datums and projections, is an essential requirement. All PINS 9000 charts are digitized and stored in Universal Transverse Mercator (UTM) coordinates for land survey convenience, then converted to Mercator lat/long coordinates for the Mariner. Most PINS 9000 charts have between 18,000 and 30,000 points, with the average chart containing approximately 1 megabyte of hydrographic chart data.

Precise vessel positioning on the electronic chart is similarly, an essential requirement. The PINS 9000 can interface with all radio or acoustic nav aids; however, to date, most PINS 9000 customers have requirements for positional accuracies of a few metres. Consequently, microwave systems have been the selected positioning system. In many cases, LORAN-C systems are used in open water until the vessel enters microwave coverage.

A user-friendly interactive keyboard is also an important consideration as many mariners are reluctant to accept a standard keyboard. The PINS 9000 keyboard consists of four fixed functions keys, eight menu select soft keys, five cursor keys and 16 numeric input keys. The PINS 9000 is a sophisticated software package with many menu selections; however, the interactive keyboard with directed syntax and menu select soft keys has proven acceptable to the Mariner.

The PINS 9000 utilizes the latest Hewlett Packard 300 Series 32-bit microprocessor computer system, a 20 megabyte mass storage system, and a medium resolution 19" colour monitor. The PINS 9000 software is written in HP Pascal and Assembler

with OSL real-time multitasking extensions to the operating system.

4.2 RADARFIX Integration

The RADARFIX computer analyzes the radar signals, computes the raw range and bearing data, then derives the vessel's position. The subsystem outputs its position via an RS232C serial data port. These values are read by the OSL PINS serial data interface and used in a Kalman filter to smooth the raw northing and easting input.

A principal objective of the NAVFIX radar positioning system was to provide a positional accuracy comparable to microwave systems. However, this also inferred by default that the system be simple to operate. During the evaluation of RADARFIX (Refer to Section 2.3) an automatic, "hands-free" start-up procedure was identified as a requirement to meet this objective.

The two modifications necessary for RADARFIX to start-up automatically were:

- a) PINS 9000 software development to emulate and replace the RADARFIX ASCII terminal; and,
- b) RADARFIX software modifications.

The ASCII terminal emulation software enabled the PINS 9000 to download the vessel's speed, gyrocompass heading and calibrated Loran-C position to the RADARFIX system. The RADARFIX modification allowed the system to accept the start-up data from the PINS 9000 and predict the vessel's position until the RADARFIX system "lock-on" to its network of radar targets.

A problem with the communications link between the PINS 9000 and the modified RADARFIX system is that there is no established protocol for unexpected display messages. RADARFIX system will transmit display messages that identify error status conditions. The conditions under which these messages are output are not consistent therefore the communications link can become corrupted and lose synchronization. To correct this problem, the RADARFIX system has to be re-initialized to get the communications link back to a known point. Fortunately, these erroneous messages do not occur often but they can be a significant annoyance to the unskilled user.

The manufacturer of RADARFIX never intended for the system to work "hands-free" all the time. It was anticipated the user would provide sufficient start-up data and manual control to initialize the radar positioning system. During the NAVFIX project, the manufacturer was not able to modify the system

to allow for proper computer control due to the limitation of the existing hardware. A new system recently released by RADARFIX addresses most of the concerns presented by OSL to the manufacturer.

4.3 PRAN Integration

The PRAN subsystem has specialized range and detection circuitry to accurately detect and measure the range and bearing to twist reflector radar targets. The acquired data are passed to the PINS 9000 electronic navigation chart display system via a general purpose input/output (GPIO) interface. The range and bearing data are decoded by the PINS 9000 to provide the range measurement in metres and the bearing measurement in degrees.

The range and bearing data in the PINS 9000 can now be used to calculate the ships position given the shore station coordinates, an estimate of the vessel's present position and the vessel's heading. However, the PRAN range data are not correlated with a given radar target as are microwave ranges to a known transponder shore station. This requires the PINS 9000 computer to determine which twist reflector has been detected. The algorithm to accomplish this task is not difficult but what complicates the problem is when several erroneous radar targets are detected and passed onto the PINS 9000 system as valid targets.

The PRAN system's static and dynamic tests indicated that the system would often detect and process several invalid targets. Spurious target detection was not limited to hostile radar clutter environments (Vancouver Harbour) but was also present, to a lesser extent, in less hostile radar clutter environments (Deep Cove). The number of unwanted range and bearings to unknown radar targets created two problems. First, it overloaded the interface buffer between the PINS 9000 system and the PRAN system. Second, it indicated that if the PRAN system was to work successfully then a sophisticated radar target tracking and gating algorithm would have to be developed.

During the evaluation phase (Refer to Section 3.7), other problems were identified with the PRAN system. These problems complicated the evaluation of the PRAN system and thus further tests on multipath fading and the adaptive threshold circuitry were not undertaken.

5.0 NAVFIX SYSTEM

5.1 Final Configuration

After evaluating the RADARFIX and PRAN subsystems it was decided that the modified RADARFIX system utilizing circular polarization and twist reflectors as radar target would be the best solution to meet Marine Atlantic's requirement for the M.V. 'ATLANTIC FREIGHTER'. The PRAN subsystem evaluation indicated that further development would be necessary to utilize the system for reliable, dynamic positioning requirements.

5.2 Port Aux Basques Installation

The modified RADARFIX system was mobilized onboard the M.V. 'ATLANTIC FREIGHTER' in August 1988 together with the PINS 9000 electronic navigation chart display system. The PINS 9000 system also integrated the ship's Loran-C receiver and gyrocompass. Located throughout the Port Aux Basques area were the MPBT twist reflectors to provide radar coverage with in the channel and on approach to Port Aux Basques. Port Aux Basques, Newfoundland is a rocky, treeless area with harsh winters and high winds. The reflector sites were predetermined by using the CRL PRAN simulation software. The preselected twist reflector sites proved to be a good starting point, however, during the course of the mobilization, several sites had to be moved and/or re-orientated.

5.3 Performance

The installed NAVFIX system was required by Marine Atlantic to be as accurate and reliable as their existing microwave system. This inferred, by default, that the system must "lock-on" automatically, provide coverage out to a minimum of 5 nautical miles and position the vessel to better than ± 5 metres. The NAVFIX system proved to be accurate but it did not provide the desired coverage and it was not able to start-up automatically on approach to Port Aux Basques.

Offshore System Ltd. was fortunately able to analyze the problems associated with the automatic start-up. Investigations indicated that the radar target network had to be improved by augmenting the MPBT twist reflectors with the larger corrugated twist reflectors and by expanding the network coverage by increasing the number of reflector sites. The other solution was related to providing a better Loran-C position to the modified RADARFIX system. The Loran-C position required a calibration offset to account for the land transmission-path effect or Additional Secondary Factor

(ASF). This offset was measured by comparing the radar position to the Loran-C determined position.

The M.V. 'ATLANTIC FREIGHTER' is now operating with the NAVFIX radar positioning system for its transit in and out of Port Aux Basques, Newfoundland. Outside of the radar target network the PINS 9000 system switches to Loran-C position automatically. On return to Port Aux Basques the system again automatically switches back to radar positioning. The accuracy and reliability of the NAVFIX system was found to be equivalent to the microwave system installed onboard the M.V. 'CARIBOU', another Marine Atlantic vessel which transits in and out of Port Aux Basques. The NAVFIX system installed onboard the M.V. 'ATLANTIC FREIGHTER' is the first dynamic, real-time reflector-based radar positioning system.

6.0 CONCLUSIONS

The advantages of radar positioning are:

- a) a network of passive retro-reflectors on shore require no electrical power, minimal maintenance and are relatively inexpensive;
- b) electrical malfunctions in the positioning system only effect the operation of one vessel in a fleet of vessels utilizing the network;
- c) all equipment is onboard and therefore simplifies the maintenance of the electronics; and,
- d) it provides an alternative to the Global Positioning System (GPS) which must be used in a differential mode to provide the accuracy required for navigation in coastal and inland waterways.

The NAVFIX project demonstrated that dynamic, real-time reflector-based radar positioning is possible. It showed that multipath fading and target-clutter discrimination remain as the principle obstacles to accurate, reliable radar navigation. Furthermore, the NAVFIX system that was delivered to Marine Atlantic and installed onboard the M.V. 'ATLANTIC FREIGHTER' is providing comparable accuracy and reliability to the microwave system installed onboard the Marine Atlantic passenger ferry, the M.V. 'CARIBOU'.

Within the investigations it was found that polarization could be exploited as a radar discriminant. The PRAN system utilized cross linear polarization whereas the modified RADARFIX system used circular polarization. Both systems were able to suppress the unwanted background radar clutter. However, the results did not clearly demonstrate that cross

linear polarization provided a significant advantage over circular polarization. Regardless which polarization is utilized, target-clutter discrimination can be significantly increased by minor increases in the size of the reflectors. A 10 percent increase in the size of the twist reflector results in a 46 percent increase in the theoretical radar cross section.

It was also noted that the cross linear polarization concept used in the PRAN system required an expensive dual-polarized antenna, cumbersome hardware and the requirement to precisely orientate the twist reflectors. The circular polarization concept used in the modified RADARFIX system required a simple modification to the standard marine radar antenna, commercially available hardware and no constraints on the mounting orientation of the twist reflectors.

The MPBT concept of silk screening silver epoxy traces on a mylar substrate for the twist reflector development proved to be a viable alternative to the copper wire grid method used by CRL. The MPBT twist reflector provided a vertical radar cross section large enough to trigger the adaptive threshold circuitry in the PRAN system. The MPBT twist reflector also provided a coherent, conspicuous radar target for the modified RADARFIX system.

The corrugated reflection surface twist reflector was found to have a slightly wider response angle than the MPBT twist reflector. It was also found that the corrugated twist reflector could be detected using cross linear polarization. Finally, the corrugated reflection surface required no dielectric and thus a radome would not be required for most applications.

Multipath fading is a major concern for the NAVFIX radar positioning system. Space diversity, a vertical separation of radar targets, is required to minimize the loss of radar signals that can have a detrimental effect on the reliability and accuracy of the system. Careful selection of radar target sites can help eliminate multipath fading and increase target-clutter discrimination by selecting sites that have less background clutter. The PRAN simulation software helped establish potential locations, however, in practice the final sites must be determined in conjunction with background clutter measurements and dynamic field trials.

7.0 RECOMMENDATIONS

Further development should concentrate on the application of radar positioning in the St. Lawrence Seaway and other areas where a network of reflectors would provide a practical and economical solution to the need for precise navigation. To this end, OSL recommends the following principal areas for further investigation:

- a) radar reflector design;
- b) reflector network design software;
- c) cross versus circular polarization; and,
- d) simplified shipboard hardware.

Each of these recommendations are discussed in the following paragraphs.

Two unique radar reflector concepts were utilized during the NAVFIX development; the corrugated reflection surface and the polarimetric transmission grid. Both worked well with circular polarization (modified RADARFIX) and cross polarization (PRAN). These two concepts should be investigated with respect to performance (radar cross section and angular response) versus production costs. Additional consideration should be given to installation techniques used to support single and multiple arrays of the radar reflectors.

Continued development of the PRAN simulation software should be supported to enhance its application as a design tool for radar reflector networks. Consideration should be given to transporting the software to a portable, generic microcomputer system thus eliminating a hardware dependence on expensive computer and display systems.

The PRAN concept of cross linear polarization requires continued development to obtain the data necessary to further evaluate its potential. This development should involve a static test with the prototype system to re-establish the proof of concept. Furthermore, circular polarization should be tested to determine its potential as a radar discriminant as compared to the cross linear approach. Additional work may include the use of radar tracking algorithms that take advantage of both the vertical and the horizontal return radar signals. Dynamic tests should then be conducted to evaluate the PRAN as an operational prototype radar positioning system.

The most significant cost reduction in hardware would be the elimination of the requirement for a separate radar to be used only for radar positioning. OSL proposes that a radar scan converter/interface could be used to take advantage of those ships fitted with circular polarized radar. The radar

scan converter output could also be integrated into the electronic navigation chart display, similar to the Shipboard Integrated Navigation And Display System (SINADS), to provide real-time radar overlay. Furthermore, if the PRAN concept is to be utilized then a simpler, more cost-effective antenna and radar system are required.

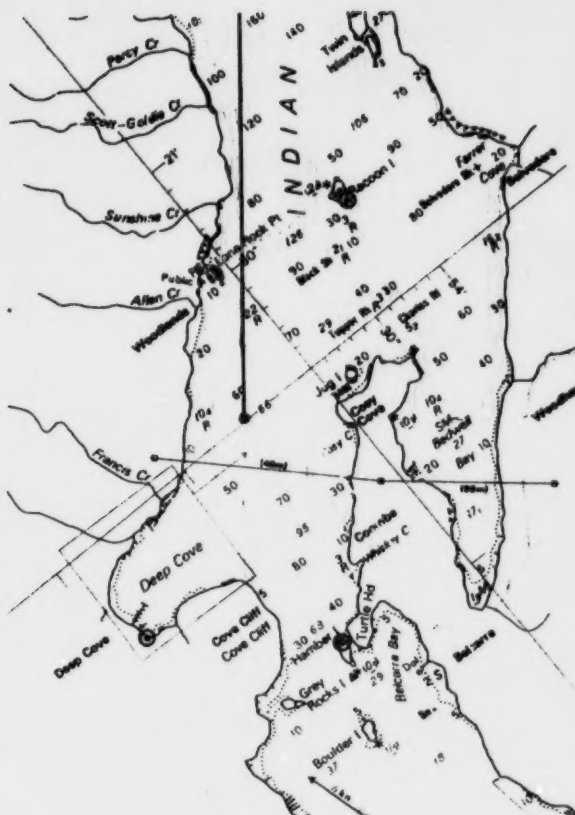


Figure 1 Standard Marine Radar Display of Deep Cove.

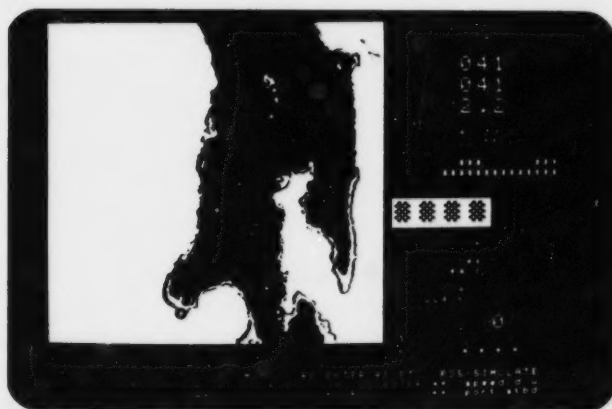


Figure 2 Section of CHS Chart showing Deep Cove and the Network of Twist Reflectors.

Pins 9000 Electronic Chart
for Deep Cove

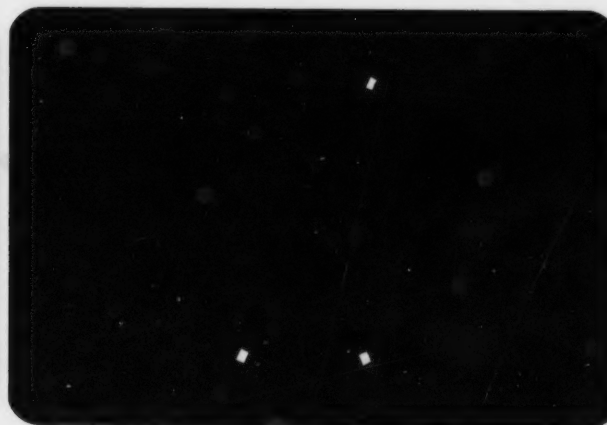


Figure 3 Modified RADARFIX Display showing Twist Reflector Echoes and Flags.

REFERENCES

1. "Proceedings of the Precise Navigation Workshop", TDC Report, TP8407E, Transportatilon Development Centre, Montreal, November 1986.
2. "An Evaluation of a Precise Radar Navigation System", TDC Report, TP2800, Dominion Marine Association, Ottawa, October 1981.
3. Greenlay, T. and Haykin, S., "On the Design of Passive Retro-Reflectors for use with Precise Radar Navigation Systems", TDC Report, TP4507, Communications Research Laboratory, McMaster University, April 1983.
4. Macikunas, A., Haykin, S. and Greenlay, T., "Trihedral Twist Reflector", patent application, Oakville, Ontario, February 1984.
5. Macikunas, A., "Passive Polarimetric Reflector for Precise Radar Navigation", M.Eng. thesis, March 1985.
6. Cho, R., Haykin, S. and Greenlay, T., "Polarimetric Radar for Precise Navigation (PRAN): Study of an Experimental System", TDC Report, TP7632E, Communications Research Laboratory, McMaster University, April 1986.
7. Virnot, A.D., "The RADARFIX Positioning System", Canadian Hydrographic Conference, Burlington, February 1987.
8. "Precise Integrated Navigation System (PINS)", TDC Report, TP7816E, Canadian Astronautics Ltd., Ottawa, July 1986, pp. 3-30 to 3-33.
9. Johnson, R. and Jasik, H., Antenna Engineering Handbook, 2nd Edition, McGraw-Hill Book Co., New York, 1984, pp. 46-10.
10. Jull, E.V., "Reflection Grating Polarisers", IEEE Transactions on Antennas and Propagation, Vol. AP-28, No.4, July 1980.
11. Skolnik, M.I., Introduction to Radar Systems, 2nd Edition, McGraw-Hill Book Co., New York, 1980, pp. 504-506.
12. Robertson, S.D., "Targets for Microwave Radar Navigation", Bell System Technical Journal, Vol.26, No.4, 1947, pp. 852-869.

APPENDIX A

Development and Field Testing of a Prototype
Polarimetric Radar for Accurate Navigation (PRAN)

**Development and Field Testing of a
Prototype Polarimetric Radar for
Accurate Navigation (PRAN)**

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Jonathan Betz designed and built the GPIO computer interface. Jerry DeBoer modified the transceiver chassis and fabricated the shipping crates.

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1. INTRODUCTION

1.1 Background

The Communications Research Laboratory (CRL) has been involved in the use of polarization diversity for marine navigation in confined waterways such as the St. Lawrence Seaway since 1982. In the initial study, it was shown that polarization diversity greatly reduces the amount of backscatter from the environment [1]. Objects which rotate the polarization of the incident pulse could easily be detected even in an environment of high background clutter. Following that study, a trihedral reflector with a twist grid to rotate the polarization of the incident radiation was invented and patented by Macikunas, Haykin and Greenlay at CRL [2,3]. The reflector-wire grid combination had an azimuthal response of approximately 20 degrees and a conversion efficiency of close to 80%. A follow up study was undertaken to determine the reflector and radar parameters for a precise navigation system based on the concept of passive polarimetric retro-reflectors [4]. The study demonstrated that a dual-polarized radar could be used to effectively discriminate between the reflectors and clutter.

A one-day workshop on precise navigation systems sponsored by the Transportation Development Centre (TDC) and the Dominion Marine Association (DMA) was held in Ottawa in November, 1986. It was concluded at the meeting that CRL's Polarimetric Radar for Accurate Navigation (PRAN) system integrated with Offshore Systems Limited's (OSL) Precise Integrated Navigation System (PINS) would offer a viable alternative to active microwave systems currently in use. The use of passive polarimetric reflectors would eliminate the need for maintenance and thus be more reliable and cost effective than active systems.

This contract is a continuation of CRL's previous work in the field of precise navigation in confined waterways.

1.2 Objectives

The objectives of this contract are:

- a. Modify the PRAN system and interface it to the OSL system to produce a precise navigation system prototype, NAVFIX.
- b. Design reflectors and an antenna according to the specifications given in [4].
- c. Install the NAVFIX system on board the OSL vessel, Offshore Surveyor, and conduct a series of static and dynamic tests in and around the Vancouver Harbour area.

- d. Demonstrate the ability of the NAVFIX system to detect the reflectors and to determine the vessel's position accurately.
- e. Install the NAVFIX system on board a Marine Atlantic vessel, the Atlantic Freighter, which runs between Sydney, Nova Scotia and Port aux Basques, Newfoundland.
- f. Set up reflector sites around the Port aux Basques area.
- g. Demonstrate the accuracy and reliability of the NAVFIX system to the user (Marine Atlantic).

1.3 Approach

To realize the above objectives, the PRAN system was modified and equipped with a signal processor to extract the range and bearing of radar targets detected. The data were passed to the OSL system for further processing. A simulation incorporating various ship, reflector and terrain parameters was developed to assist in determining the reflector sites for the Port aux Basques area.

The NAVFIX system was installed on board the Offshore Surveyor in North Vancouver, British Columbia. Reflector sites were set up in and around Vancouver Harbour and Deep Cove. A series of static and dynamic tests were conducted to evaluate the performance of the NAVFIX system.

2. TRANSCEIVER MODIFICATIONS

2.1 Introduction

The original PRAN system consisted of two Racal/Decca RM1229 marine radar units connected to an antenna with a dual-polarized feed. The antenna, with a 1.2 metre parabolic dish, produced a pencil beam with a 3 dB beamwidth of 1.5 degrees in azimuth and elevation and thus was not suitable for marine applications.

One radar unit was used to transmit and receive the like-polarized signal. The second unit was used exclusively to receive the cross-polarized signal. Consequently, most of the circuitry in the second radar unit was unnecessary. It was decided to retain, from the second unit, only the components required to receive the RF energy and extract the video signal; and repackage it along with the first unit in a single housing. This not only made the system more compact but reduced the power requirements as well, from three rectifiers to two.

The Plan Position Indicator (PPI) was retained to provide control signals to the transceiver unit and to aid in troubleshooting and finetuning the system. A remote control panel will be incorporated into the PRAN unit to make the PPI unnecessary. This will also reduce the number of rectifiers required to one.

2.2 Primary Transceiver Components

The primary components of the transceiver are, Figure 2.1 :

- a. magnetron
- b. modulator unit
- c. power supply unit
- d. receiver section and support stand
- e. TR cell
- f. mixer
- g. local oscillator

In view of the discussion in section 2.1, the only components required to receive the cross-polarized signal are the receiver section and support stand, TR cell and mixer. The TR cell protects the receiver against damage from high power signals. The mixer combines the output from the local oscillator with the received signal to produce the intermediate frequency (IF) signal from which the video is extracted. These components along with the transmit/receive radar are repackaged into a single unit. The sections below discuss the modifications incorporated into the final version of the system.

2.3 Zero Range Reference

In order to obtain an accurate range measurement, the range of a target must be measured relative to a reference point along the signal path between the magnetron and the antenna feed. For ease of access and protection, it was decided to fix the reference point inside the transceiver unit. A cross-guide directional coupler was inserted between the magnetron and the unit housing. The direction coupler with a 40 dB coupling was fitted with a 20 dB SMA attenuator and a Schottky diode detector.

As the RF pulse from the magnetron passes through the directional coupler, a small amount of the energy (-40 dB) is redirected through the attenuator to the detector. When the detector senses the RF energy, a voltage is produced which is compared to a threshold value. The range counter is enabled if the detector output exceeds the threshold. When the length of the waveguide run between the transceiver and the antenna is known, the range of the target with respect to the reference point (diode detector) can be accurately determined.

2.4 Local Oscillator

The local oscillator operates at a frequency slightly different from the signal frequency produced by the magnetron. When the two signals are combined in the mixer, the result is the IF signal, 60 MHz in our case. Since there is one signal source, the magnetron, and two receiver sections, the same local oscillator should be used to ensure the IF signals from the like- and cross-polarization channels are at the same frequency. Only then can a fair comparison be made between the two channels to properly assess the effectiveness of the reflectors and the CHL antenna.

To accomplish this, the local oscillator was connected to a hybrid tee. The hybrid tee is a 4-port coupling device. The receiver sections were connected to two of its ports, the collinear arms, and the fourth port was terminated. This resulted in the signal from the local oscillator being split equally between the two receivers with very little loss. To have the proper orientation and alignment between the hybrid tee and the receivers, 90 degree waveguide bends, twists and a two inch flexible waveguide section were inserted between the tee and the receivers.

2.5 Receiver Sections

The receiver sections were installed side by side in the new housing. The receiver section for the horizontal or like-polarization can be easily identified as the magnetron is connected to its support stand. Power and control signals for the second receiver section (vertical or cross-polarization) are derived from the first receiver.

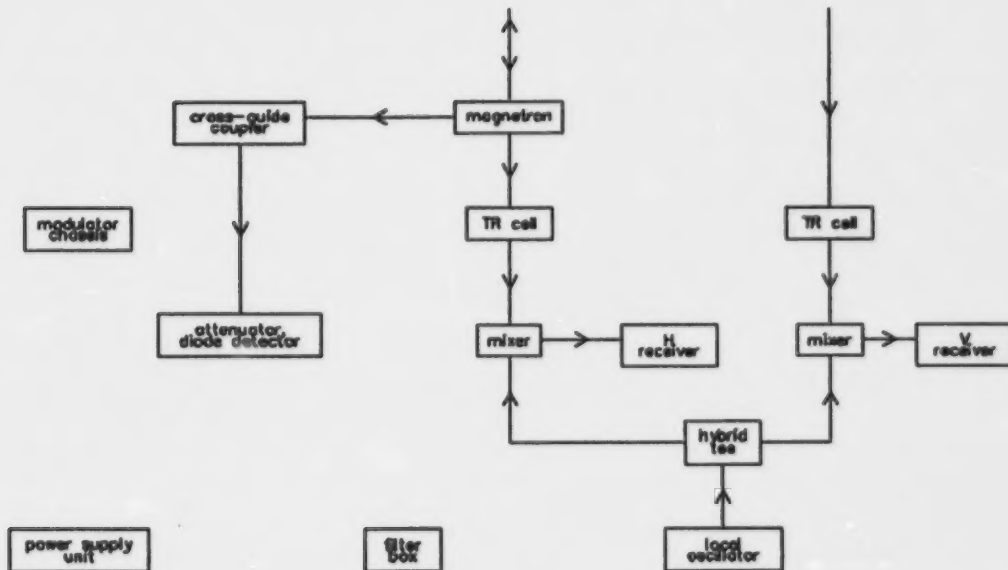


Figure 2.1 Principal Components of Modified Transceiver

3. GPIO COMPUTER INTERFACE

3.1 Introduction

The GPIO computer interface consists of 4 printed circuit boards mounted on the metal plate that shields the RF components in the transceiver housing, Fig. 3.1. The functions of the interface are to provide the external trigger to the transceiver, perform target detection on the video signal and output the range and bearing of targets detected to the PINS 9000 system. The individual boards are described below.

3.2.1 Circuit Board One

Board 1, Fig. 3.2, contains the video and zero range comparators, counter control and the 16-bit range counter latches.

The zero range mark is defined to be the point at which the output from the diode detector in the transceiver exceeds a fixed threshold value. The zero range mark enables the range counter which is incremented at 50 MHz or every 20 nanoseconds (ns). This corresponds to a range resolution of 3 metres. The 50 MHz timing signal is generated on board 2.

The video signal and threshold value are compared by the video comparator to determine if a target is present. The video comparator uses a variable threshold supplied by boards 3 and 4. The range, 0-11640 m, is divided into 32 steps. The first step is 480 m and the next 31 steps are increments of 360 m. The threshold values form a step function that decreases as $1/R^4$ where R is the range. This, very roughly, removes the range dependence of the signal. Depending on the range of the sample being tested, the threshold is changed accordingly.

If the video exceeds the threshold, the range and bearing are latched and sent to the PINS 9000. The value stored in the range counter latches represents the number of clock pulses that have occurred between the time the zero range comparator enabled the counter and when a target was detected. The range is a 15-bit data word (0-32767). This is converted into the actual range in metres in PINS. Due to the high speed and power consumption of the range latches (ECL), a cooling fan was mounted on the underside of the board with the flow of air directed over the chips by a vent.

3.2.2 Circuit Board Two

Board 2, Fig. 3.3, provides the external trigger to the transceiver, the timing signals for the interface and the GPIO handshaking for the transfer of data to the PINS 9000.

The oven-controlled crystal oscillator is used to provide a highly stable reference signal of 5 MHz. This reference signal is used to externally trigger the magnetron. The pulse repetition frequency (PRF) is given by

$$5 \text{ MHz} / 16 / N$$

where N is between 95 and 999. The PRF then ranges from approximately 312 to a maximum of 3300. The PRF should not exceed 3300 to prevent overdriving the magnetron. The series of DIP switches on the board are set to a value equal to $1000 - N$, Figure 3.4. The range given for N in Figure 3.4 assumed a maximum PRF of 1500.

The oscillator is also used as the reference signal in the phase lock loop. The reference frequency is phase compared to a voltage controlled oscillator output which has been divided down by a factor of 10. The resultant 50 MHz signal is as stable as the reference signal. This 50 MHz signal is used to clock the range counter on board 1.

The range and bearing of targets detected are sent to the PINS 9000 via the GPIO interface cable (50-conductor ribbon cable). The GPIO handshaking and setting of control lines are handled on this board. The range and bearing data are sent as 16-bit words.

3.2.3 Circuit Board Three

Board 3, Fig. 3.5, contains the STC control, STC D/A and the azimuth decoding circuitry. The STC or sensitivity time control is used to maintain a constant echo signal strength by removing the range dependence of the signal.

The STC control circuitry uses the reference signal, 5 MHz, in a counter to generate the 32 STC addresses used on board 4 to obtain the correct threshold value. The 8-bit threshold value is retrieved from board 4 and converted into an analog signal with the STC D/A. This is supplied to the video comparator on board 1 for testing the radar video.

The azimuth circuitry decodes the information from the optical shaft encoder into a 12-bit azimuth value (0-4095). This is converted into the actual bearing in PINS.

3.2.4 Circuit Board Four

Board 4, Fig. 3.6, has 32 buffers that contain the detection threshold values. The threshold value in each buffer is individually set by its eight corresponding DIP switches. The buffers on the board are numbered top to bottom, right to left. The resultant STC curve can be viewed on an oscilloscope by attaching a probe to the STC test point on board 1, Fig. 3.7. The STC address decoder is used to access the proper buffer given the address from board 3. The corresponding threshold value is sent to the STC D/A on board 3.

3.3 Signal Sequence

The 5 MHz reference signal from the crystal oscillator is divided down according to the setting of the DIP switches to obtain the proper PRF. An external trigger pulse is generated to fire the transmitter. As the outgoing RF pulse passes the crossguide coupler, a small portion of the RF energy is coupled to the diode detector. The detector outputs a voltage proportional to the RF energy received. The zero range comparator on board 1 is used to test the detector output against the fixed threshold value. The range counter is enabled when the threshold is exceeded.

The STC address of the variable threshold value is generated on board 3. The address is sent to board 4 where it is decoded. The threshold value in the corresponding buffer is sent to the STC D/A on board 3. The resultant analog signal is used by the video comparator on board 1 to test the video signal. If the sample exceeds the threshold value, a reflector is assumed to have been detected and the range counter is latched.

The azimuth circuitry on board 3 supplies the bearing information for each sweep. When a target has been detected, the range counter value and the bearing are latched and sent to the PINS 9000 via the GPIO interface cable as two 16-bit data words.

3.4 Operation of the GPIO Computer Interface

When power is applied to the interface, the cooling fan on the underside of the interface should be checked to ensure that it is working properly. The GPIO switch, Fig. 3.1, should be left in the off (down) position until the computer is ready to receive the range and azimuth data.

Test points have been provided on boards 1 and 2 to allow the STC curve, trigger and the radar video to be monitored on an oscilloscope. The STC and video test points are located on board 1, Fig. 3.7, and the trigger test point is located on board 2, Fig. 3.1. When the STC curve is being monitored, the oscilloscope should be triggered from the trigger test point.

The radar video gain can be adjusted by the VIN Gain potentiometer on board 1, Fig. 3.7. Increasing the gain (turn clockwise) raises the video level relative to the STC or detection threshold. This will result in an increase of background clutter and hence more 'targets' being detected. The setting of this pot should be adjusted for minimum background clutter and still allow the reflectors to be detected.

It should not be necessary to adjust the STC curve since reducing the video level has the same effect as increasing the STC and vice versa. However, should it be necessary to adjust the curve, each value in a buffer is set by 8 DIP switches on board 4 with the left DIP switch being the most significant bit. Each threshold value ranges from 0 to 255 (8 bits) and the shape of the curve can be monitored on a scope from the STC test point as it is being changed. The buffers on board 4 are arranged top to bottom, right to left. Therefore the set of DIP switches located at the upper right hand corner of the board corresponds to the first buffer or the first range gate. The set of DIP switches at the bottom left hand corner corresponds to the thirty-second buffer or the last range gate.

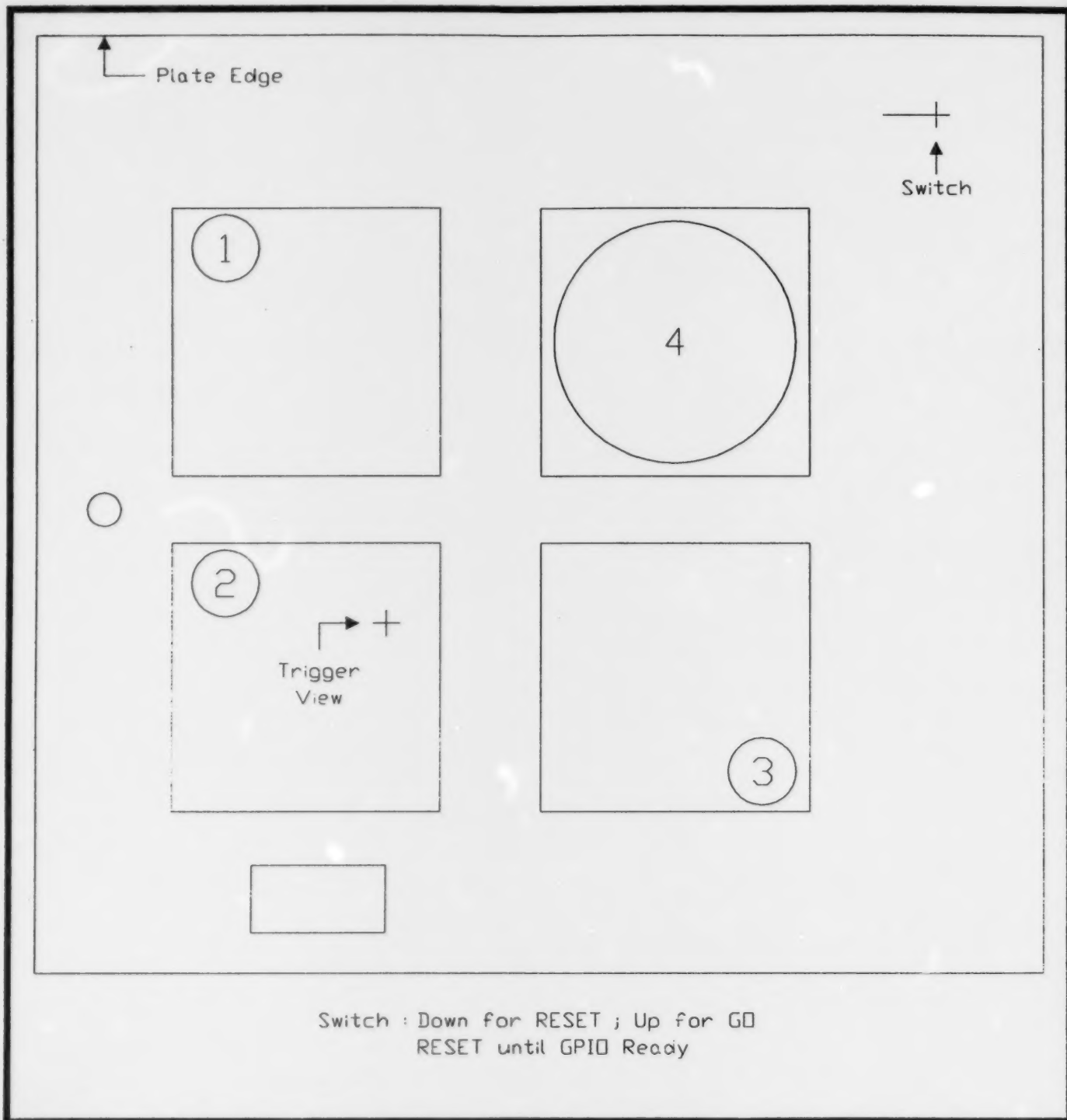
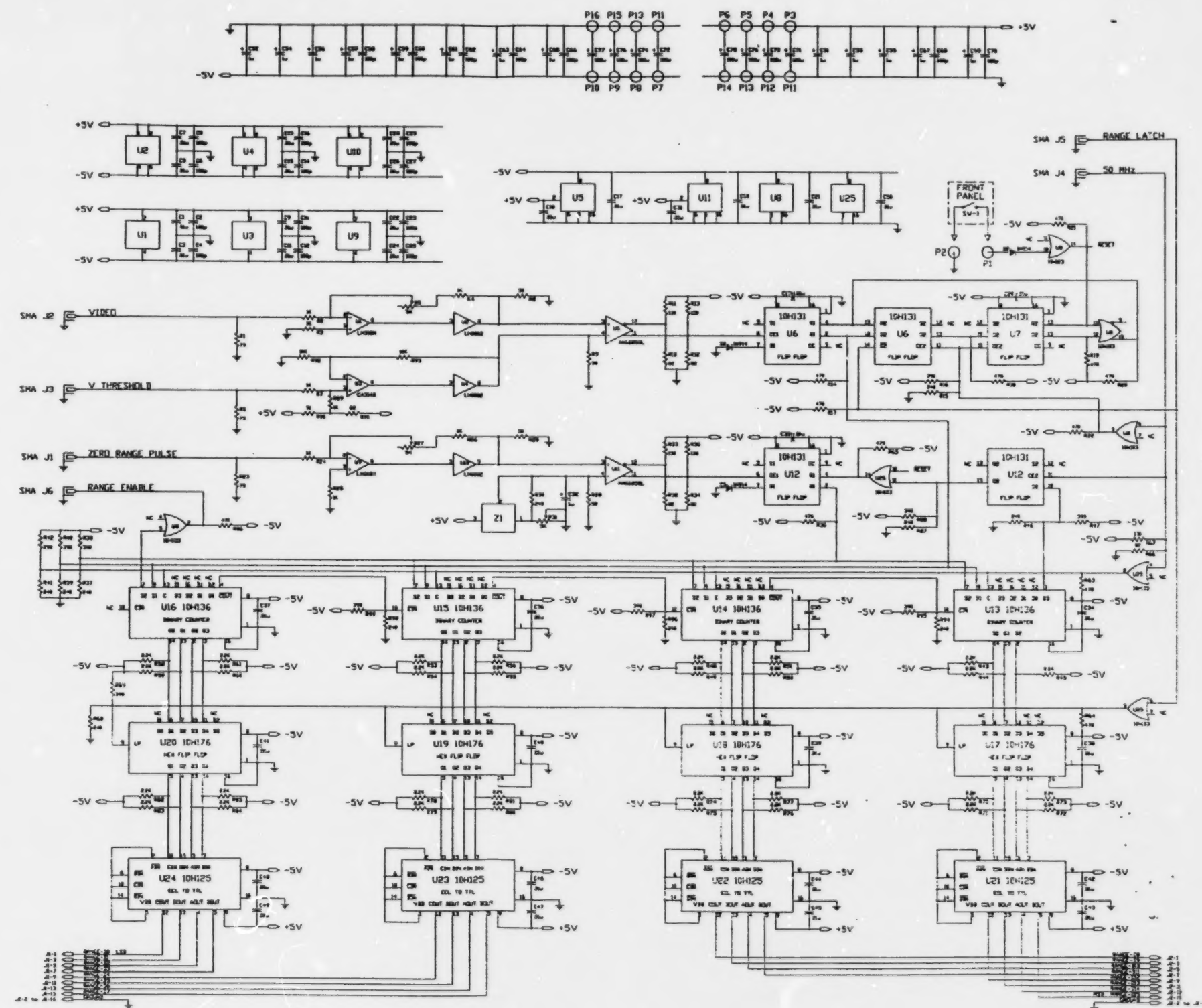


Figure 3.1 GPIO Computer Interface Layout
(Prepared by Jonathan Betz)

Figure 3.2 Schematic Diagram of Board 1

NOTES:

- SV-1:
- 1/2 of DPST Momentary Switch for Manual Reset
- Z1:
- Adjustable Voltage Regulator
- SHA J1:
- From Transceiver
- SHA J2:
- From Transceiver
- SHA J3:
- From SHA J2 on PRAN-1.3
- SHA J4:
- From SHA J4 on PRAN-1.1
- SHA J5:
- To SHA J6 on PRAN-1.1
- SHA J6:
- To SHA J3 on PRAN-1.3
- J1:
- 16 Pin Flat Cable Header
- To J1 on PRAN-1.1
- J2:
- 16 Pin Flat Cable Header
- To J2 on PRAN-1.1
- P1 to P16:
- Solder Posts



REFERENCES:
REVISIONS:

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TARGET DETECTION
COMPARATORS
COUNTER/LATCHES

ID: PRAN-12

VERSION: 1.00

DATE: 08/09/87

PAGE: (D) 2 OF 6

SCALE: NTS

DRAWN BY: JPB

SCHEMATIC FILE:
SPRAN-12.DWG



)

Figure 3.3 Schematic Diagram of Board 2

NOTES:

- PRE-TRIGGER:
 - High Pulse 1 usec. long
- TRIGGER:
 - High Pulse 1 usec. long
 - Delayed by 18 usec. from Pre-Trigger
- L1:
 - Miller Core T-25-12
 - 5 Turns of 24 Gauge Wire
- SIG23-w:
 - 6 Pin SIP Resistor
 - 0

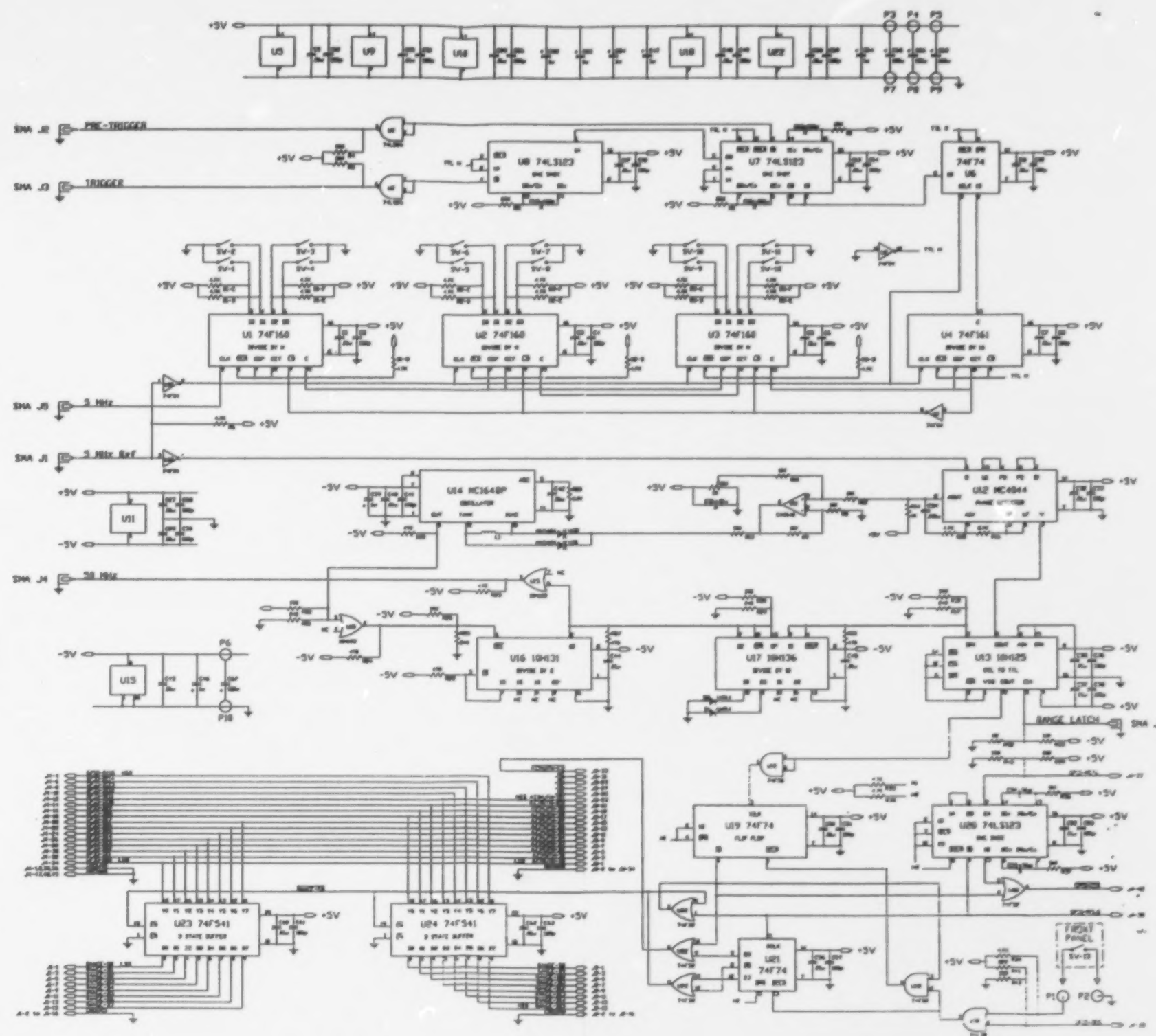
0

0

0

0

0
 - A Connected to +5V
- SV-1 to SV-12:
 - Miniature PCB Switches
- SV-13:
 - 1/2 of DPST Momentary Switch for Manual Reset
- SHA J1:
 - From Crystal Oscillator
- SHA J2:
 - To Analog Recorder
- SHA J3:
 - To Transceiver
- SHA J4:
 - To SHA J4 on PRAN-12
- SHA J5:
 - To SHA J1 on PRAN-13
- SHA J6:
 - From SHA J5 on PRAN-12
- J1:
 - From J1 on PRAN-12
 - 16 Pin Flat Cable Header
- J2:
 - From J2 on PRAN-12
 - 16 Pin Flat Cable Header
- J3:
 - From J3 on PRAN-13
 - 34 Pin Flat Cable Header
- J4:
 - To P1 on HP 98622A
 - GPIB Interface
 - 50 Pin Flat Cable Header
- P1 to P10:
 - Solder Posts



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PLO / HP98622A
 . TRIGGERS
 GPIB CONTROL

ID:PRAN-1.1

VERSION:1.00

DATE:28.06.01

PAGE:(D):1 of 5

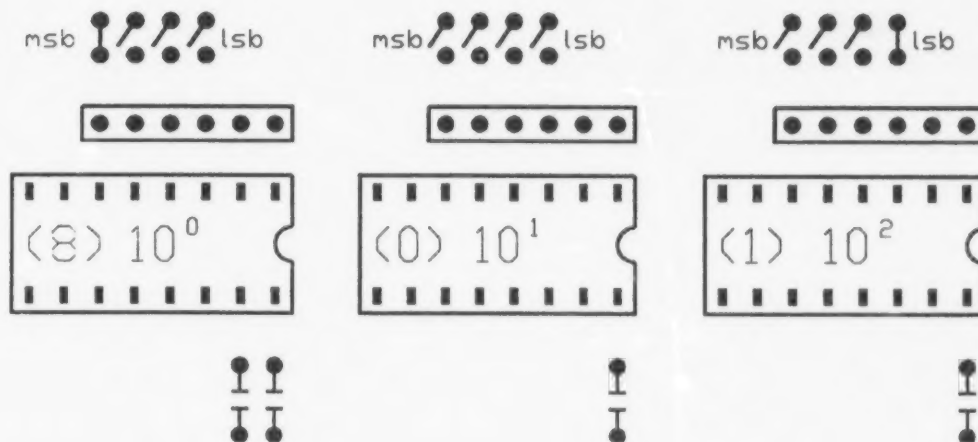
SCALE:NTS

DRAWN BY:JPB

SCHEMATIC FILE:
 SPRAN-11.DWG

Board Edge

Note : Switch Up is a 1
Switch Down is a 0



PRF = 5 MHz / 16 / N where
N is a number from 208 to 999
Switch settings = 1000 - N
EG : 350.3 = 5 MHz / 16 / 892
1000 - 892 = 108

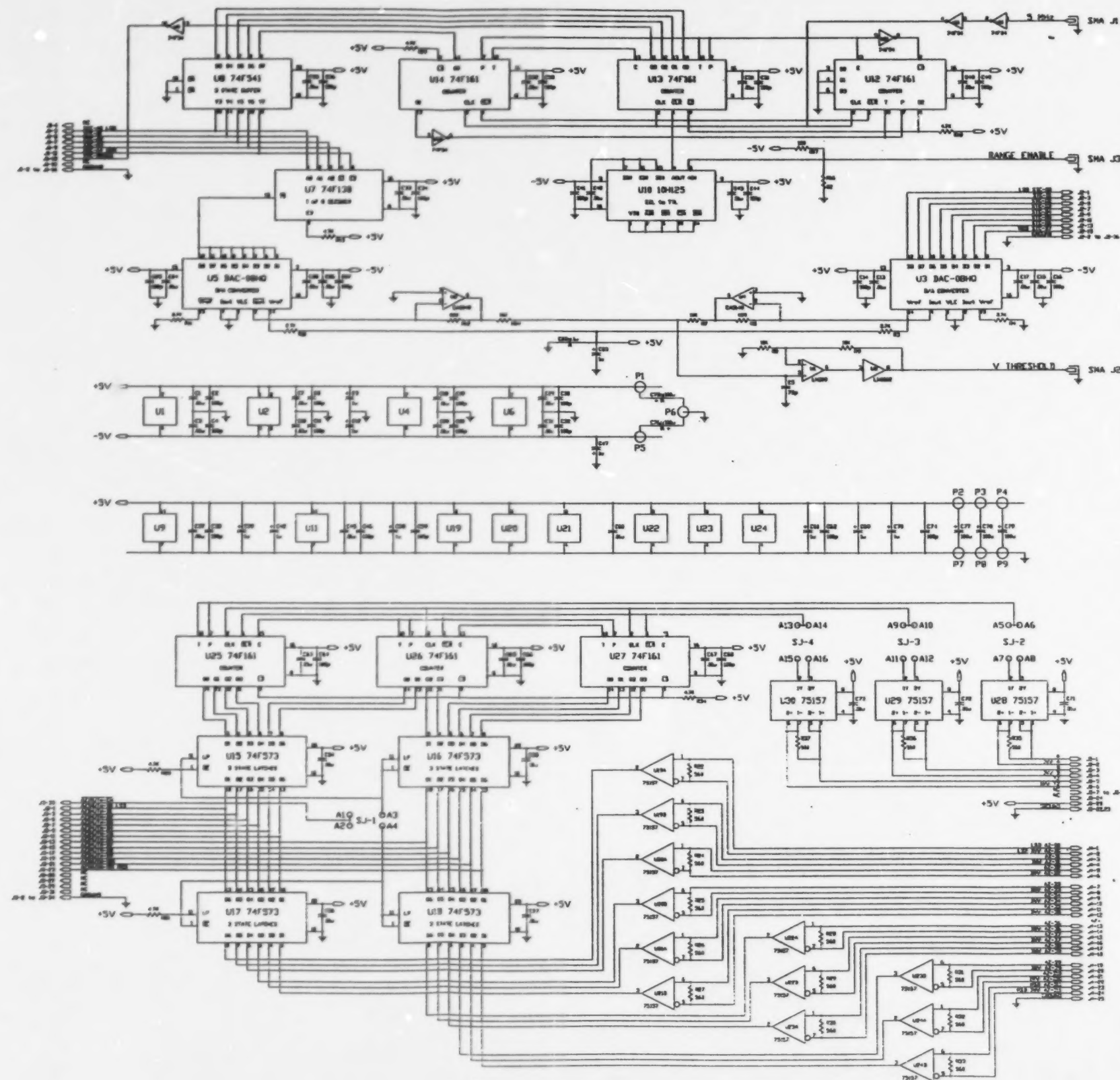
2

Figure 3.4 PRF DIP Switches
(Prepared by Jonathan Betz)

Figure 3.5 Schematic Diagram of Board 3

NOTES:

- Z1: - Adjustable Voltage Regulator
- SMA J1: - From SMA J5 on PRAN-11
- SMA J2: - To SMA J3 on PRAN-12
- SMA J3: - From SMA J6 on PRAN-12
- J1: - From J1 on PRAN-14
- 16 Pin Flat Cable Header
- J2: - To J2 on PRAN-14
- 16 Pin Flat Cable Header
- J3: - To J3 on PRAN-11
- 34 Pin Flat Cable Header
- J4: - From Sector Blanking
- 26 Pin Flat Cable Header
- J5: - From Optical Encoder
- 26 Pin Flat Cable Header
- P1 to P9: - Solder Posts
- A1 to A16: - Jumper Posts
- SJ-1: - Shorting Jack to select which azimuth is sent to the HP98622A
- SJ-2: - Shorting Jack to select the high true counter enable
- SJ-3: - Shorting Jack to select the high true counter clock
- SJ-4: - Shorting Jack to select the low true counter clear



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STC/AZIMUTH
 D/A and COUNTER
 BUFFER or COUNTER
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 VERSION: 1.00
 DATE: 88.06.01
 PAGE: (1) of 6
 SCALE: NTS
 DRAWN BY: JPB
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 SPRAN-13.DWG

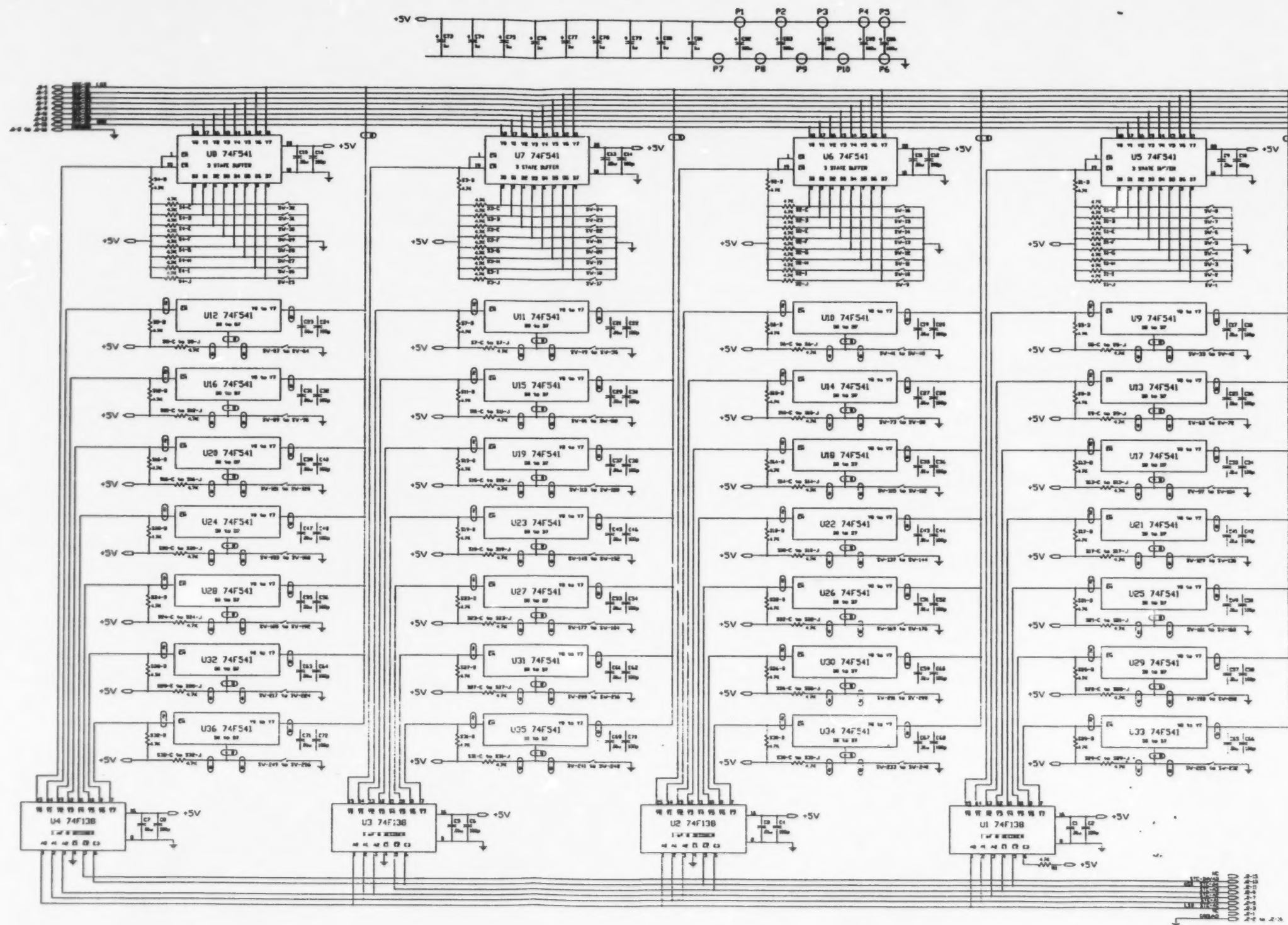


Figure 3.6 Schematic Diagram of Board 4

NOTES:

- U9 to U36
- Not shown in full detail
- Refer to Schematic of U5/U6, U7 or U8 for Full Details
- S1-x to S32-x
- 10 Pin SIP Resistor
- *****
- A Connected to +5V
- SV-1 to SV-256
- Miniature PCB Switches
- J1
- 16 Pin Flat Cable Header
- To J1 on PRAN-1.3
- J2
- 16 Pin Flat Cable Header
- From J2 on PRAN-1.3
- P1 to P10
- Solder Posts

REFERENCES: REVISIONS:

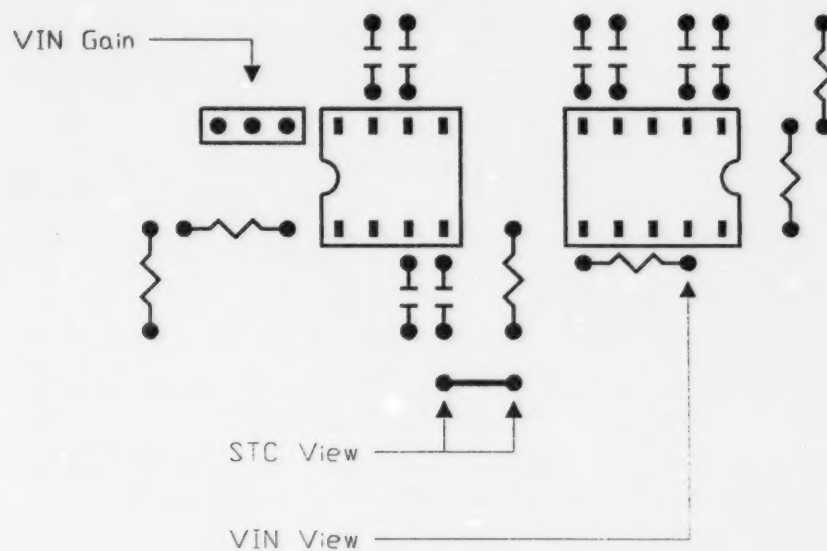


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STC
BUFFERS
DECODERS
ID: PRAN-1.4
VERSION: 1.00
DATE: 08/06/01
PAGE: (D) 4 of 6
SCALE: NTS
DRAWN BY: JPB
SCHEMATIC FILE:
SPRAN-14.DWG



Board Edge



1

Figure 3.7 STC Test Point
(Prepared by Jonathan Betz)

4. SIMULATION SOFTWARE

4.1 Introduction

The problem of selecting reflector sites for a given stretch of waterway or harbour has a number of requirements and constraints that makes any manual attempt extremely difficult and time consuming.

The requirements are that the reflector sites must provide adequate coverage over the entire length of the channel. The term 'adequate' usually implies four reflectors to be visible at each point along the channel but no less than two since this is the minimum number required for a position fix. To minimize the positioning error, the geometry of the reflectors must be good in the sense that the reflector bearing lines should intersect at an angle as close to 90 degrees as possible. A reflector bearing line is a line from the reflector site along the direction the reflector is pointing. Maximum error occurs when two reflector bearing lines are collinear.

The reflector sites must be accessible with a clear line-of-sight to the channel. The reflectors at each site must be positioned properly in height so that as the vessel sails through the coverage area, multipath is minimized. The reflectors have a 3-dB response of approximately 20 degrees in azimuth. Assuming the bearing line of a reflector is perpendicular to the channel, the coverage provided by the reflector is approximately $0.35d$ where d is the distance from the reflector site to the channel. If a reflector site is 1 km from the channel, then that site can cover only a 350-metre stretch of the channel. To reduce the number of sites, the reflectors should be placed as far back from the channel as possible. This, however, increases the likelihood of conflict with the requirements of accessibility and an unobstructed view. It would be difficult if not impossible to find a set of reflector sites such that each requirement is satisfied in an optimal manner.

With the above requirements and constraints in mind, a simulation package was created to aid in the selection of reflector sites. The selection of sites is highly dependent on the nature of the area under consideration and it is doubtful whether one can come up with a set of rules general enough to apply in all situations.

The terrain elevation of the area is required to drive the simulation. A map of the Port aux Basques area was digitized using the Eikonix Image Digitizer. A separate program was

used to enter the terrain elevation. The sections below give a description of the routines in the simulation package.

4.2 Description of Programs LSQZ and SIM

The simulation software is made up of two programs. The first program, LSQZ, contains routines to aid in the selection of reflector sites and to determine the reflector heights at each site. Once the channel or vessel tracks have been established and the sites selected, the second program calculates, for each point along the channel, the position error taking into account the ship motion, reflector geometry and various radar and terrain parameters. Descriptions of the individual subroutines are presented in Appendix A and program listings in Appendix B.

The program LSQZ requires as input a digitized map image of the area, the radar frequency and the height of the antenna. Selecting various routines from the menu, the graphics tablet cursor is used to generate vessel tracks and to position reflector sites, Fig. 4.1. The region of reflector coverage can be displayed on the screen to let the user see the section of the channel being covered by the reflector site, Fig. 4.2. As well, a list of possible reflector heights to minimize the multipath problem is displayed. At present each site contains two reflectors. The user can also choose various routines to determine the reflector sites visible in azimuth and elevation for a given test point. A check for multipath is made as well. The reflector-ship-reflector angle can be obtained using one of the routines and the cursor to specify the reflectors and ship positions. This provides a quick check of the suitability of the geometry of the reflector sites. The coordinates of the channel and reflectors, coverage areas and the reflector heights are stored in two data files that will be used by the second program, SIM.

In addition to the two files created by the above program, the program SIM also requires a number of parameters describing the radar, antenna, vessel and reflector characteristics. These parameters can be entered from the keyboard in response to prompts or they can be stored in a data file and read in by the program. The program SIM uses the method of least squares to calculate the position error for each point along the channel. At each test point, the pitch and roll angles of the ship are updated to simulate a moving vessel. A list of reflector sites visible in azimuth and elevation is generated. A 'detection' of these sites is performed taking into

account the ship-reflector aspect angle, multipath and the modified antenna beam pattern. The ship-reflector aspect angle is used to vary the reflector radar cross section. The multipath propagation factor is calculated to determine its effects on the received signal strength. The antenna beam pattern is modified due to the pitch and roll motion of the vessel, which has the effect of tilting the antenna. Thus the part of the beam that illuminates the reflector is different from that with no vessel motion i.e. a stationary platform. All these factors affect the detection performance of the system. The sites that are detected are used by the least-squares method to determine the position error. The results are stored in a data file that can be displayed on the high resolution Ramtek graphics system, Fig. 4.3.

4.3 Usage of Program LSQZ

To use the simulation package to determine reflector sites for an area, a map of the area must first be digitized to obtain the terrain elevation. This information is required by various routines to calculate the reflector heights, multipath propagation factors, etc.

The routine RDWI is used to read the map data into an array and display the image on the Ramtek display. Working from the display, the graphics tablet cursor is used to plot the channel with the routine VESSEL_TRK. The start and end points of each section of the channel or stretch are stored in a data file.

It is easier to work with individual stretches of the channel when fixing the reflector sites. Reflectors should be located close to roads whenever possible for ease of access. Multipath is minimized when the reflector bearing lines are perpendicular to the channel. This results in the least amount of range change over the reflector coverage area. There should be enough overlapping coverage between consecutive stretches so that waypoints do not pose a problem. The routine REF_POS is used to position the reflector sites. Routines REF_COV and REF_HT are called to calculate the reflector coverage and reflector heights, respectively. The reflector coordinates, bearing and heights are stored in a data file.

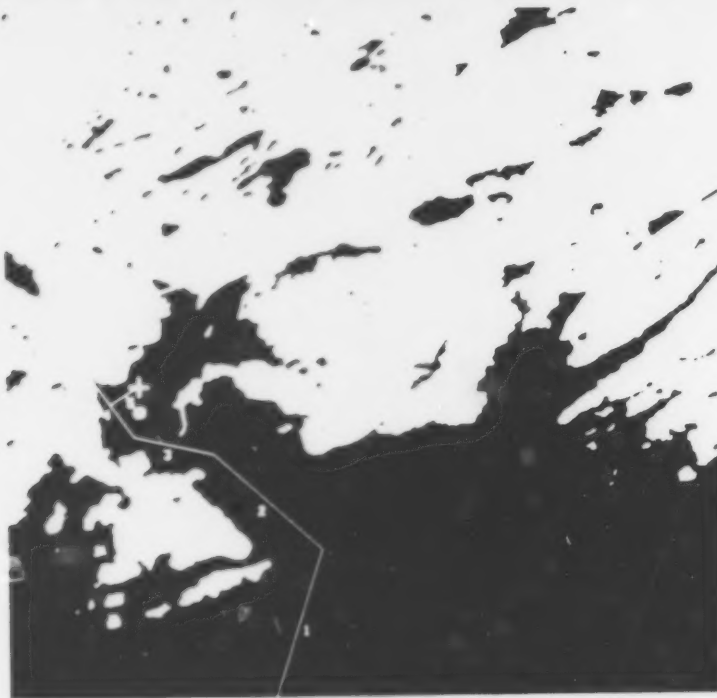


Figure 4.1 Port aux Basques and Channel

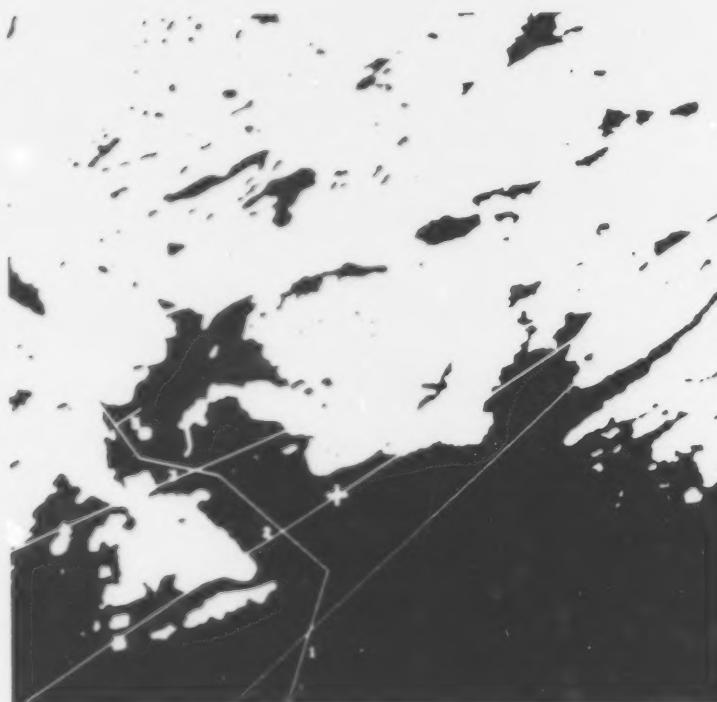


Figure 4.2 Reflector Bearing and Coverage

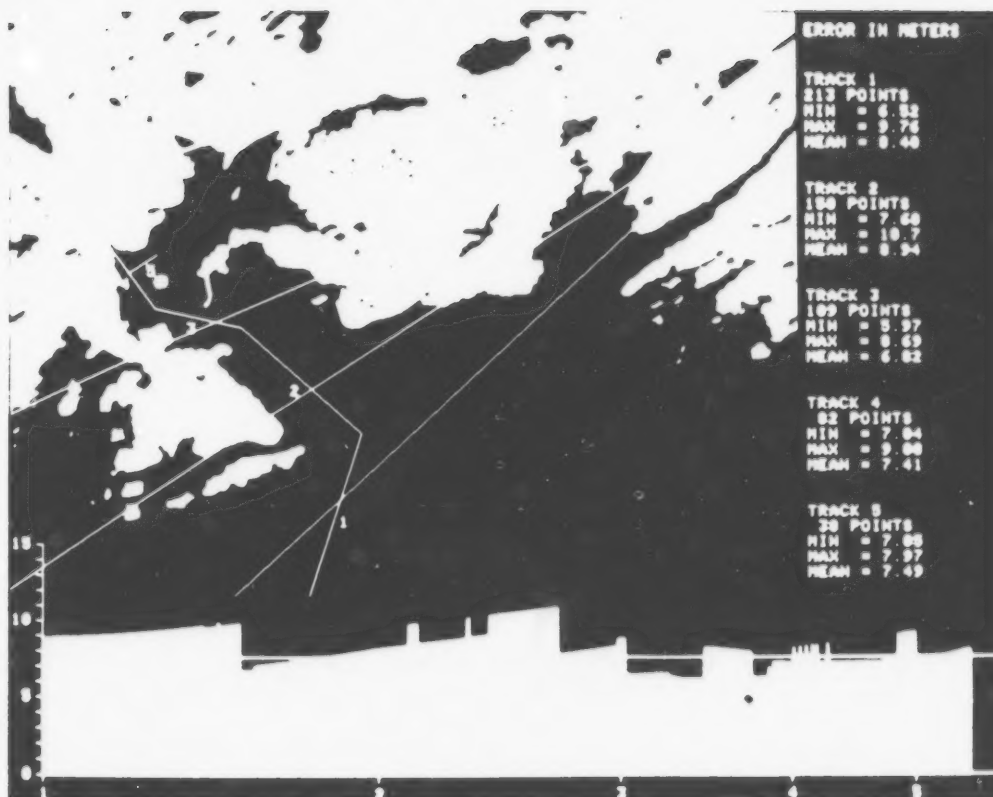


Figure 4.3 Error Display for Port aux Basques

5. REFLECTOR TESTING

5.1 Introduction

The design, construction and testing of the reflectors were subcontracted to MPBT Technologies, Inc. of Montreal by OSL. The technique chosen to construct the wire grid used silk screening to lay down silver epoxy traces on a mylar substrate. MPBT, however, did not follow the recommended parameters for the twist grid and consequently the test results were not what was expected [5]. At a meeting held in February, 1988, in Montreal to discuss the reflector parameters and the test results, there was disagreement between MPBT and CRL as to the interpretation of the test results and also what constituted a good measure of the wire grid conversion efficiency. Following that meeting, OSL decided to produce the wire grids according to the recommended parameters using the silk screening process. MPBT manufactured the trihedral reflectors and CRL performed the testing on the reflector and wire grid prototypes.

5.2 Wire Grid Parameters

The recommended wire diameter for the grid was 0.05 mm. However, it was not possible to obtain traces of this width using the silk screening process. The smallest width possible was 0.1 mm. Therefore it was necessary to experiment with the wire spacing and the height off the reflector surface given the new trace width. See section 2.4 of [4] for a description of the test procedure.

OSL had 14 grids made up using two different trace widths. The wire spacing for width 0.1 mm ranged from 6.5 mm to 9.5 mm. The wire spacing for width 0.2 mm ranged from 8.5 mm to 11.5 mm. Each grid was tested using different spacings off the reflector surface. Three of these graphs for the best grid are shown in Figure 5.1. These graphs show the reflector-grid response over the frequency range from 9 to 10 GHz for separations of 1.6, 1.7 and 1.8 cm. The top trace corresponds to the reflector without a grid. The centre and bottom traces correspond to the cross and like polarizations of the reflector with a grid respectively. It was found that the best results, Fig. 5.1b, were obtained using a grid with the following parameters:

trace width - 0.1 mm

wire spacing - 6.5 mm

distance off reflector surface - 17 mm

When the distance between the grid and the reflector surface was changed from 17 mm, the separation between the top two traces increased indicating a decrease in the grid conversion efficiency.

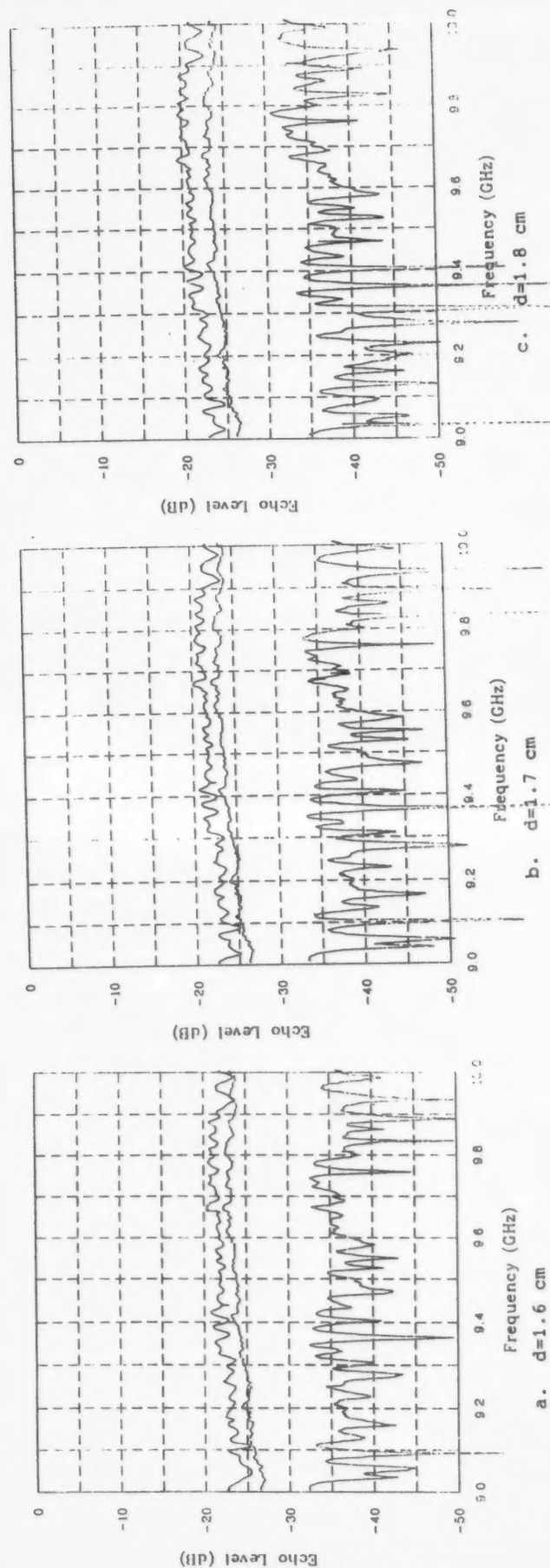


Figure 5.1 Reflector Signal as a Function of Twist Grid-Reflector Separation

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6. VANCOUVER SEA TRIALS

6.1 Introduction

The PRAN system consisting of a PPI display, transceiver unit with two receiver sections and two rectifiers was shipped to OSL in North Vancouver, British Columbia. It was interfaced to the CHL antenna and the PINS 9000 on board the Offshore Surveyor. Static and dynamic tests were carried out in the Vancouver Harbour area and at Deep Cove.

6.2 Installation

The CHL antenna is a dual-polarized antenna with an azimuth beamwidth of 0.92 degrees and an elevation beamwidth of 18.4 degrees. The antenna gain is 32.7 dB and the cross-polarization rejection is greater than 30 dB. The antenna rotates at 24 revolutions per minute and the bearing information is obtained from the optical shaft encoder which outputs 4096 pulses per revolution. The CHL antenna pedestal was mounted on the deckhead of the wheelhouse. Twelve-inch flexible waveguide sections were used to connect the transceiver unit to two lengths of WR-90 rigid waveguide. The two rigid sections were passed through a hole in the wheelhouse deckhead, up the inside of the antenna pedestal and connected to the antenna below the motor housing. A cable carrying the bearing information from the optical shaft encoder was also passed down the pedestal and connected to the GPIO computer interface.

The two rectifiers were mounted on a bulkhead in the wheelhouse. The PPI, transceiver and rectifiers were connected together. The GPIO computer interface was connected to PINS via a 50-conductor ribbon cable.

The DB-25 connector of the cable carrying the information from the optical shaft encoder was rewired to make the pin layout consistent with the ribbon cable on board 3 of the GPIO computer interface. The inverter board, 65121BT, in the PPI was damaged, possibly during shipping, and had to be replaced. Two relative bearing analog signals are required to drive the PPI while the output from the optical shaft encoder is digital. Hence the CHL antenna could not be used to drive the PPI directly. A CHL/PPI bearing interface board was used to convert the digital output from the shaft encoder into analog signals required by the PPI. It was found that the signal from the antenna could not be used to drive the board and the GPIO computer

interface at the same time. A 3-wire connector was added to the system to disconnect the CHL/PPI bearing interface board quickly when switching from the PPI to the OSL display.

The PINS software was modified to display objects that exceeded the detection threshold. Each detection was indicated by a pixel at the corresponding range and bearing on the display.

6.3 Static Tests

The Offshore Surveyor was docked at the Lynnwood Marina in North Vancouver. Two MPBT reflectors were mounted on a support stand and placed approximately 750 metres away across a stretch of open water. A large steel bridge ran parallel to the propagation path and to within 100 metres of the reflector site. Grain elevators were on the other side of the site. The reflectors were set close to the water and aimed directly at the antenna. The video gain control on board 1 of the GPIO computer interface was adjusted to eliminate as much of the background clutter as possible so as to isolate the reflectors.

The testing took place over several days. Depending on the tide at the time of the test, the signal from the reflectors varied greatly. By scanning the reflectors over an extended period of time, the signal from the reflectors could be observed to strengthen and weaken relative to the background clutter as the tide changed.

6.4 Dynamic Tests

A pair of reflectors was set up in Vancouver Harbour. Due to the marine traffic in the harbour, it was not possible to sail straight at the reflectors over a long distance or to stop at one spot for any length of time to observe the effects of multipath.

Four reflector sites were set up around the Deep Cove area. Two of the sites were on islands. The third site was on top of a building in Deep Cove. This site consisted of one MPBT reflector on the roof and one OSL reflector above it on a scaffold. The OSL reflectors are different in design and construction and are much larger than the MPBT reflectors. One MPBT reflector was placed at the fourth site, Panorama Park. The two island sites had one OSL reflector each.

Various boat maneuvers were conducted at Deep Cove to observe the effects of multipath on the detection of reflectors. Again, the gain control on the GPIO computer interface was adjusted to minimize the background clutter.

7. RESULTS

7.1 Sea Trials in Vancouver

The preliminary static and dynamic tests conducted were all of a qualitative nature. These tests were used to troubleshoot and tune the system and to gain a better understanding of the multipath problem encountered on board a moving platform.

In the static tests, it was sometimes possible to reduce the gain control to the point where only the reflectors appeared on the display. However, most of the time a few strong reflection points on the bridge were also detected. This was to be expected since the bridge, about 150 to 200 metres away, had many trihedral and dihedral reflectors formed by the steel girders. Its large size and closeness made it difficult to suppress the bridge entirely. The number of reflection points detected on the bridge varied with the time of day the observation was made. The tide altered the multipath pattern and hence the signal strength of the reflectors. This in turn limited our ability to adjust the video gain level to minimize the background clutter.

In the dynamic tests conducted in Vancouver Harbour, more background clutter appeared on the display. It was not possible to adjust the gain control to eliminate all of the clutter without eliminating the reflectors as well. Since we could not vary the height of the reflectors and the movement of the Offshore Surveyor was restricted by the traffic in the area, it was not possible to determine the multipath pattern and whether the observed reflector signal strength was near a maximum or minimum. It is likely that if the reflectors had been adjusted properly, the amount of background clutter observed could have been reduced considerably though not completely eliminated.

In the tests conducted at Deep Cove, the system performed much better than in Vancouver Harbour due to a more benign environment. By adjusting the gain control, it was possible to eliminate virtually all of the background clutter. In the various maneuvers with the Offshore Surveyor it was possible to track and detect the reflectors on the roof of the Deep Cove building consistently. This was due to the size of the OSL reflector and the fact that the array of two reflectors minimized the effects of multipath. The two island sites were visible most of the time although not as consistently as the building site. Again, each island site had only one OSL reflector resting on the ground so multipath caused the reflectors to fade in and

out during the maneuvers. The site with the single MPBT reflector was not as consistent as the other three sites but during some of the maneuvers it performed quite well. The reflector is much smaller than the OSL reflectors and it was also affected by multipath.

Without the ability to vary the height of the reflectors to obtain a maximum in the multipath pattern, it is not very meaningful to discuss the relative signal strengths of the reflectors and the background clutter. When clutter appears along with the reflectors on the display, it is not possible to determine in an absolute sense whether or not the clutter is stronger than the reflectors without a knowledge of the multipath pattern.

There was some concern as to why the image on the OSL display was different from the one on the PPI display. The video signal going to the PPI is identical to the signal going to the detection circuitry in the GPIO computer interface. However the detection curve used by the GPIO computer interface is different from the STC curve in the PPI. The use of the different curves resulted in slightly different processed images.

7.2 System Specification for Port aux Basques

The channel at Port aux Basques was divided into five stretches. The parameters used in the simulation are given in Table 7.1. To simulate the dynamics of a moving vessel, the values of 1.5 and 5 degrees were used as the maximum pitch and roll angles respectively. The pitch and roll periods were assumed to be 8 and 10 seconds respectively. The detection performance of the system is dependent on the pitch and roll of the ship since the antenna platform is not stabilized. Large pitch and roll values result in the antenna being highly tilted and decrease the probability of a target being seen in the centre of the beam.

The positioning accuracy is determined using the method of least-squares [6]. This method is used to give a unique solution in an overdetermined system. The accuracy of a position fix is dependent on the reflector geometry and the measurement errors i.e. the error in range and the error in the reflector site coordinates. Each range-range measurement results in a slightly different ship position due to the measurement errors. The least-squares method estimates a unique position such that the sum of the distances of the calculated positions from the estimated position is minimized. The range error used in the simulation was 3 m, which corresponded to the system sampling rate of 50 MHz. The reflector site coordinates were

assumed to be accurate to 2 m. These errors along with the geometry of the reflector sites limit the accuracy of a position fix.

The reflector edge length was assumed to be 0.61 m and twenty degrees was used for the angular response of the reflector.

A total of eight sites, 2 reflectors per site, were required to give adequate coverage. The sites were positioned close to the Trans-Canada Highway for ease of access, Figures 7.1 and 7.2. The terrain elevation and reflector heights for each site are given below.

Site	Terrain Elevation (m)	Reflector Height (m)
1	3	22.66, 25.49 ¹
2	46	50.21, 52.00
3	30	33.84, 36.29
4	32	34.22, 36.20
5	46	49.25, 51.20
6	3	5.48, 7.99
7	46	48.63, 50.66
8	76	79.79, 82.99

The results from the program SIM are given below, Figures 7.3 and 7.4. For each stretch, the minimum, maximum and mean error of the position error are given.

Stretch	Position Error (metres)			Sites visible
	Min	Max	Mean	
1	6.52	9.76	8.40	1,2,6,7,8
2	7.60	10.72	8.94	1,2,4,6,8
3	5.97	8.69	6.62	1,5,6,7,8
4	7.04	9.08	7.41	1,3,7,8
5	7.05	7.97	7.49	1,3,7,8

¹Reflector heights dependent on possible church attachment points.

The position errors are plotted across the bottom of the figure. The line parallel to the x-axis is a user specified threshold. Channel positions with errors exceeding the threshold are displayed. Not all of the sites indicated are visible at every point for the corresponding stretch. However a minimum of two sites are always visible.

From the graphs of the position errors, Figs. 7.3 and 7.4, we see that the error suddenly increased from approximately 7 m to 8 m for six points near the beginning of track 4. This is caused by the fading of reflector site 7 i.e. no detection. This would suggest that to minimize the position error, an additional site is required.

There are a number of ways to reduce the positioning error. Optimizing the geometry of the reflector sites is one but that may not always be possible. The measurement errors can be reduced by increasing the sampling rate of the system and reducing the error in the reflector site coordinates by more exact surveying techniques. Table 7.2 shows the position errors if the reflector sites coordinates were known exactly. Increasing the system sampling rate results in a more accurate determination of the peak of the signal or target. This, however, would also depend on the threshold, system calibration, radar waveform and the receiver bandwidth.

The accuracy of the position fix can also be improved by using the range-bearing information instead of the range-range data. Let R , e_r and e_b be the target range, range error and bearing error, respectively. The angular error increases with range as the product $R \cdot e_b$. The range, R_0 , at which the angular error is equal to the range error is given by

$$R_0 \cdot e_b = e_r \quad \text{or} \quad R_0 = e_r / e_b.$$

If the target range is greater than R_0 ,

$$R > R_0 = e_r / e_b \quad \text{or} \quad R \cdot e_b > e_r,$$

then the angular error is greater than the range error. If the target range is less than R_0 ,

$$R < R_0 = e_r / e_b \quad \text{or} \quad R \cdot e_b < e_r,$$

then the angular error is less than the range error. Therefore, when the target is closer than or equal to the distance $R_0 = e_r / e_b$, the range-bearing information is more accurate.

Table 7.1

Radar
 power - 20 kW
 frequency - 9.4 GHz
 PRF - 3300

Antenna
 gain - 30 dB
 beamwidth:
 azimuth - 1 deg
 elevation - 20 deg
 RPM - 24
 height - 20 m

Vessel
 pitch period - 8 s
 roll period - 10 s
 max. pitch angle - 1.5 deg
 max. roll angle - 5 deg

Errors
 range accuracy - 3.0 m
 reflector coords - 2.0 m

Table 7.2

Stretch	Position Error (metres)			Sites visible
	Min	Max	Mean	
1	5.43	8.12	6.99	1,2,6,7,8
2	6.32	8.92	7.44	1,2,4,6,8
3	4.96	7.23	5.68	1,5,6,7,8
4	5.86	7.56	6.16	1,3,7,8
5	5.87	6.63	6.23	1,3,7,8

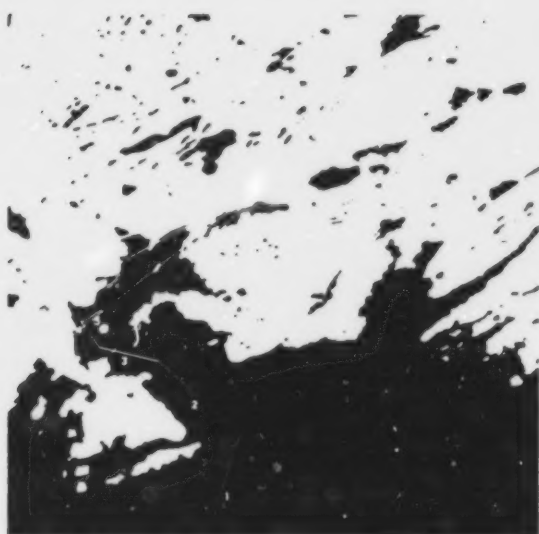


Figure 7.1 Reflector Sites 1-4 (clockwise from upper left)

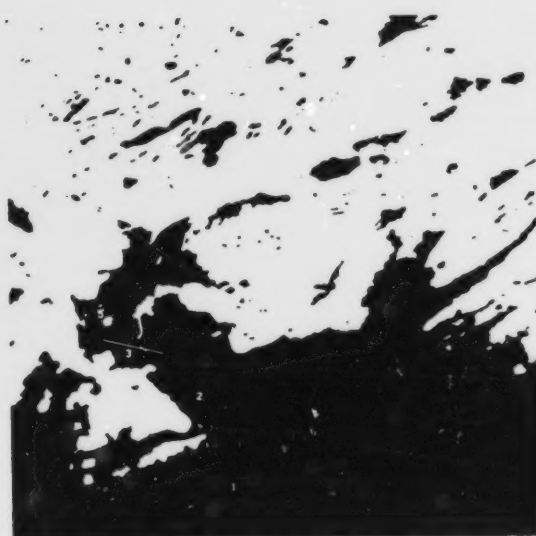
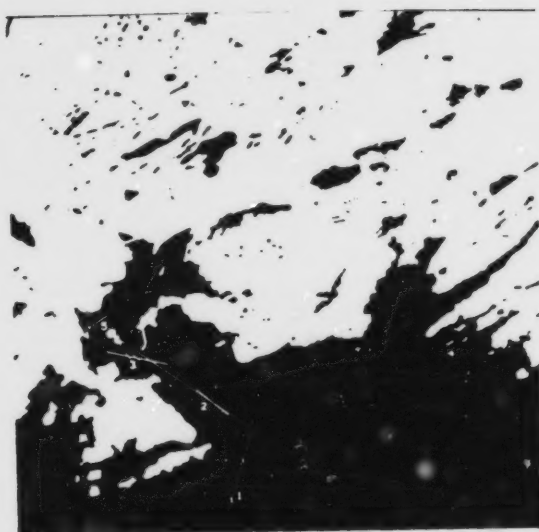


Figure 7.2 Reflector Sites 5-8 (clockwise from upper left)



Figure 7.3 Error Display, threshold = 7.5 m

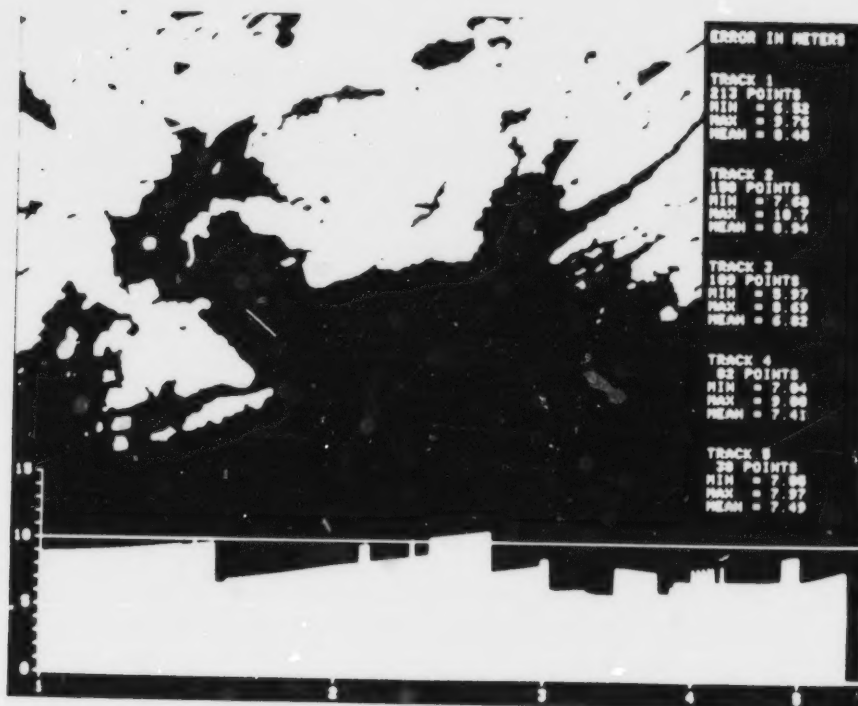
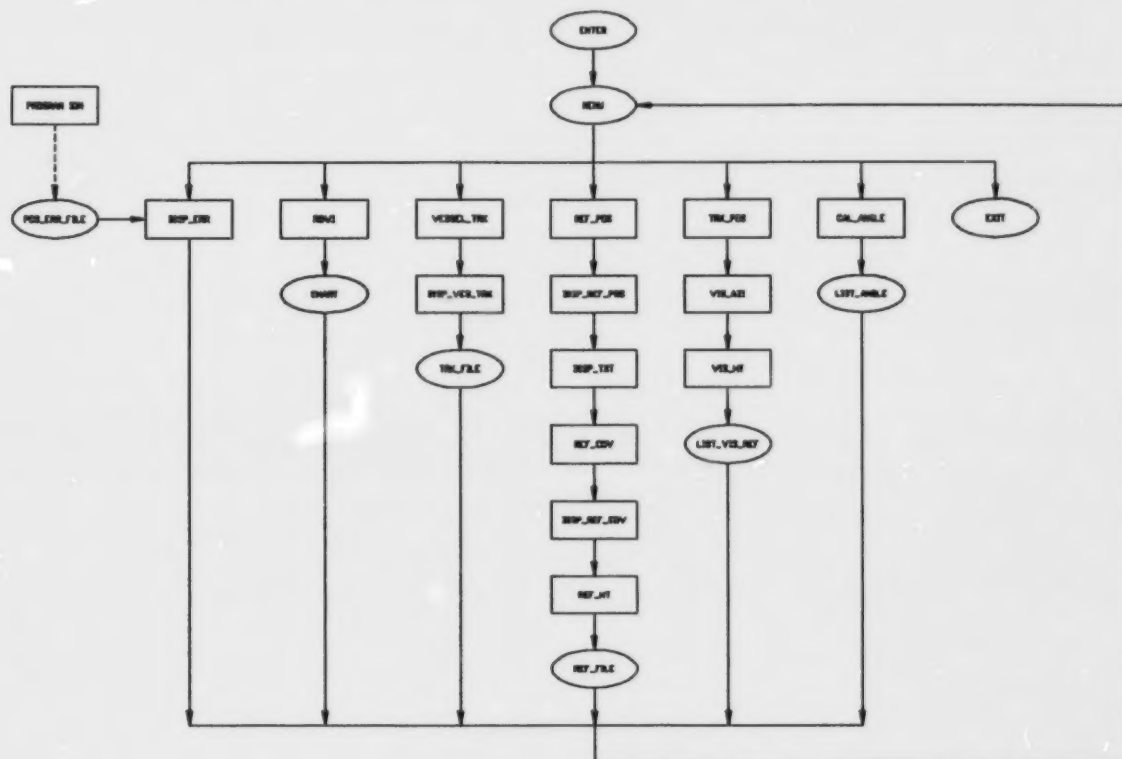


Figure 7.4 Error Display, threshold = 10.0 m

APPENDIX A

Program LSQZ

This is the main program that calls up a menu of the different routines available. The subroutines labelled with "*" can be called in any order using the menu.



Subroutine **RDWI** *

This subroutine reads a digitized map image of the area from a data file into an array and writes the image to the Ramtek display, Figure 4.1. The value of each pixel in the image is its elevation. This is used in other routines to test for possible terrain obstructions and to calculate the proper reflector heights.

Subroutine **VESSEL_TRK** *

The user creates probable vessel tracks using the graphics tablet and cursor to specify start and end points for the tracks, Figure 4.1. The track coordinates are written to a data file.

Subroutine DISP_VES_TRK *

Displays the vessel tracks on the Ramtek using one of the overlay planes.

Subroutine REF_POS *

The user defines reflector locations and bearing using the cursor, Figure 4.2. The line connecting a user specified second point to the reflector position gives the reflector bearing line or the direction the reflector is pointing.

Subroutine REF_COV

Calculates the reflector coverage area based on the reflector 3 dB azimuthal response, Figure 4.2.

Subroutine REF_HT

Calculates the required reflector heights to obtain maximums in the multipath pattern taking into account the terrain elevation, height of the antenna and the range. The routine calculates the intersection of the three rays (coverage area) with the channel to determine the minimum and maximum range for the multipath calculations. In the manual mode, the cursor can be used to specify the intersection points and hence change the coverage region.

Subroutine DISP_REF_POS *

Displays and numbers the reflector positions on the Ramtek using one of the overlay planes.

Subroutine DISP_REF_COV *

Displays the reflector coverage areas on the Ramtek using one of the overlay planes.

Subroutine CAL_ANGLE *

Calculates the angle subtended by two reflectors at a user specified test point. This is used to check the geometry of the reflectors.

Subroutine VIS_AZI

Creates a list of all the reflectors visible in azimuth at a user specified test point.

Subroutine VIS_HT

Creates a list of all the reflectors unobstructed by terrain from the list supplied by the subroutine VIS_AZI. A check for multipath is made.

Subroutine TRK_POS *

Calls subroutines VIS_AZI and VIS_HT to provide a list of reflectors visible in both azimuth and elevation for test points specified by the user.

Subroutine DISP_TXT

Displays text on the Ramtek. Called by various subroutines.

Subroutine DISP_ERR *

Displays the data generated by program SIM on the Ramtek using one of the overlay planes, Figure 4.3. The minimum, maximum and mean position errors are given for each stretch of the channel. The graph on the bottom plots the position error for each point along the channel. The line parallel to the x-axis is a user specified error threshold. Channel positions with errors exceeding the threshold are displayed, Figs. 7.3 and 7.4. By displaying the SIM data, the user can determine how the position accuracy varies with different simulation parameters and where the critical channel points are i.e. positions that exceed the error threshold.

Subroutine RM_EMP *

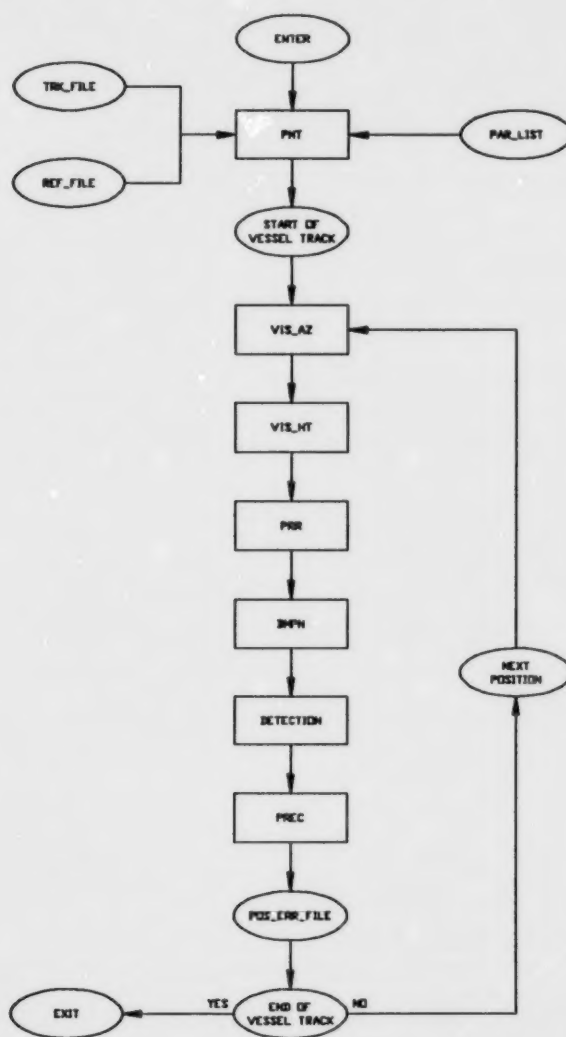
Erases selected memory planes in the Ramtek.

Subroutine RM_BERS *

Erases all the memory planes in the Ramtek.

Program SIM

This is the main program that performs the error calculations using the subroutines below.



Subroutine PMT

This subroutine accepts parameters for the ship motion, antenna, radar system and reflectors from either the terminal or a data file, e.g. Table 7.1.

Subroutine PRR

Calculates the pitch and roll angles of the ship given the pitch and roll periods and the maximum pitch and roll angles. The motions are approximated by two sinusoids.

Subroutine **BMPN**

Calculates the antenna gain in the direction of the reflectors given the pitch and roll angles of the ship and the rotation of the antenna relative to the ship's heading.

Subroutine **DETECTION**

Using the list of reflectors from the subroutines VIS_AZI and VIS_HT, it determines whether a reflector is detectable taking into account the modified antenna beam pattern, multipath and the aspect angle of the ship relative to the reflector. The reflector radar cross section is dependent on the aspect angle.

Subroutine **PREC**

Calculates the position accuracy of points along the channel given the reflector geometry using least squares approximation and stores the results in a data file. The results can be displayed on the Ramtek using the subroutine DISP_ERR in program LSQZ.

APPENDIX B

Program Listings

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NAME:
PROGRAM LSQZ

PURPOSE:
Simulation to locate reflectors

PROGRAM LSQZ
IMPLICIT INTEGER*2 (I-N)
INTEGER*2 OFFSET
CHARACTER TXT*80
COMMON /BLK7/ WL,AHGT

WRITE(6,('1'," Radar frequency (GHz)"))
READ(5,*) WL
WL=.3/WL I Radar wavelength
WRITE(6,('//'," Height of antenna"))
READ(5,*) AHGT

CALL RMASIN(ICHAN) I Allocate ramtek, logical channel

CALL MENU(ICODE)

DO WHILE (ICODE.NE.0)

IF (ICODE.EQ.1) THEN
CALL RDWI(ICHAN,OFFSET) I Display image, store in MAP

ELSE IF (ICODE.EQ.2) THEN
CALL VESSEL_TRK(ICHAN,OFFSET,TXT)

ELSE IF (ICODE.EQ.3) THEN
CALL REF_POS(ICHAN,OFFSET,TXT)

ELSE IF (ICODE.EQ.4) THEN
CALL CAL_ANGLE(ICHAN)

ELSE IF (ICODE.EQ.5) THEN
CALL TRK_POS(ICHAN,OFFSET)

ELSE IF (ICODE.EQ.6) THEN
CALL DISP_VES_TRK(ICHAN,OFFSET,TXT)

ELSE IF (ICODE.EQ.7) THEN
CALL DISP_REF_POS(ICHAN,OFFSET,TXT)

ELSE IF (ICODE.EQ.8) THEN
CALL DISP_REF_COV(ICHAN,OFFSET,TXT)

ELSE IF (ICODE.EQ.9) THEN
CALL DISP_ERR(ICHAN,OFFSET,TXT)

ELSE IF (ICODE.EQ.10) THEN
CALL RM_EMP(ICHAN)

```

ELSE IF (ICODE.EQ.11) THEN
    CALL RM_BERS(ICHAN)

ELSE
    WRITE(6,'/, " Selection out of range")
END IF

CALL MENU(ICODE)

END DO

CALL RMDSIN(ICHAN)

STOP
END

SUBROUTINE MENU(ICODE)
IMPLICIT INTEGER*2 (I-N)

WRITE(6,'/')
WRITE(6,'/,5X,"0 - Stop")
WRITE(6,'/,5X,"1 - Display map image on Ramtek")
WRITE(6,'/,5X,"2 - Define vessel track(s)")
WRITE(6,'/,5X,"3 - Reflector positioning and coverage")
WRITE(6,'/,5X,"4 - Reflector geometry")
WRITE(6,'/,5X,"5 - Reflectors visible along track")
WRITE(6,'/,5X,"6 - Display vessel tracks")
WRITE(6,'/,5X,"7 - Display reflector positions")
WRITE(6,'/,5X,"8 - Display reflector coverage")
WRITE(6,'/,5X,"9 - Display error calculations")
WRITE(6,'/,4X,"10 - Erase overlay plane(s)")
WRITE(6,'/,4X,"11 - Bulk erase")
READ(5,*) ICODE

RETURN
END

```


WI(5)=XMAXRAM
WI(6)=YMAXRAM

NP1=YMAXRAM+1-OFFSET
WI(8)=NP1*2

DO J=0, XMAXRAM

WI(3)=J

!Ramtek x (col) coord

CALL RMOUT2(ICHAN,WI,8,MAP(OFFSET,J),NP1)
END DO

END IF

RETURN
END

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NAME:
SUBROUTINE VESSEL_TRK

PURPOSE:
Define and display vessel track(s), ram coords

CALL:
CALL VESSEL_TRK(ICHAN,OFFSET,TXT)

WHERE:
ICHAN - Logical channel number
OFFSET - Data offset
TXT - Text string

SUBROUTINE VESSEL_TRK(ICHAN,OFFSET,TXT)
IMPLICIT INTEGER*2 (I-N)
INTEGER*2 TRACK(20,4),OFFSET
CHARACTER TXT*80,FNAME*20,ANS*1
COMMON /BLK3/ TRACK,NTRK

WRITE(6,'/'," Read track information from file ? (Y/N)")
READ(5,'(A)') ANS

IF (ANS.EQ.'Y'.OR.ANS.EQ.'y') THEN

WRITE(6,*) 'Input file'
READ(5,'(A)') FNAME
OPEN(1,FILE=FNAME,STATUS='OLD',ACCESS='SEQUENTIAL')
READ(1,*) NTRK
DO I=1, NTRK
READ(1,*) (TRACK(I,J),J=1,4)
END DO
CLOSE(1)

WRITE(6,'/'," Display vessel tracks ? (Y/N)")
READ(5,'(A)') ANS
IF(ANS.EQ.'Y'.OR.ANS.EQ.'y') CALL DISP_VES_TRK(ICHAN,OFFSET,TXT)

ELSE

NTRK=0
N=1

WRITE(6,'/'," Track number, 0 to stop")
READ(5,*) N

DO WHILE (N.GT.0)

IF (NTRK.LT.N) NTRK=N
WRITE(6,'/'," Track",I3)' N
DO I=1, 2
WRITE(6,*) 'Position cursor'
READ(5,*)
CALL RM_RCSP(ICHAN,IX0,IY0)

```

        TRACK(N,2*I-1)=IX0
        TRACK(N,2*I)=IY0
    END DO
    CALL DISP_VES_TRK(ICHAN,OFFSET,TXT)

    WRITE(6,'//," Store track coords ? (Y/N)"')
    READ(5,'(A)') ANS
    IF (ANS.EQ.'N'.OR.ANS.EQ.'n') THEN
        TRACK(N,1)=0
        TRACK(N,2)=0
        TRACK(N,3)=0
        TRACK(N,4)=0
    END IF

    WRITE(6,'//," Track number, 0 to stop"')
    READ(5,'(A)') N

    END DO

    END IF

    WRITE(6,'//," Write track coords to file ? (Y/N)"')
    READ(5,'(A)') ANS

    IF (ANS.EQ.'Y'.OR.ANS.EQ.'y') THEN
        WRITE(6,*) 'Output file'
        READ(5,'(A)') FNAME
        OPEN(1,FILE=FNAME,STATUS='NEW',ACCESS='SEQUENTIAL')
        WRITE(1,*) NTRK
        DO I=1, NTRK
            WRITE(1,*) (TRACK(I,J),J=1,4)
        END DO
        CLOSE(1)
    END IF

    RETURN
END

```


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NAME:
SUBROUTINE DISP_VES_TRK

PURPOSE:
Display vessel track(s), ram coords

CALL:
CALL DISP_VES_TRK(ICHAN,OFFSET,TXT)

WHERE:
ICHAN - Logical channel number
OFFSET - Data offset
TXT - Text string

SUBROUTINE DISP_VES_TRK(ICHAN,OFFSET,TXT)
IMPLICIT INTEGER*2 (I-N)
INTEGER*2 TRACK(20,4),OFFSET
CHARACTER TXT*80
COMMON /BLK3/ TRACK,NTRK

CALL RM_EMP(ICHAN)

DO I=1, NTRK

IF (TRACK(I,1).NE.0.AND.TRACK(I,2).NE.0.AND.
& TRACK(I,3).NE.0.AND.TRACK(I,4).NE.0) THEN

CALL RM_WVU(ICHAN,TRACK(I,1),TRACK(I,2)-OFFSET,
& TRACK(I,3),TRACK(I,4)-OFFSET,1024)

IF (I.LE.9) THEN
WRITE(TXT,'(I1)') I
J=1
ELSE
WRITE(TXT(1:2),'(I2)') I
J=2
END IF

CALL DISP_TXT(ICHAN,1024,'0101'X,
& TRACK(I,1),TRACK(I,2)-OFFSET,J,TXT)

END IF

END DO

RETURN
END


```

DO I=NREFP1, 20
  DO J=1, 14
    REF(I,J)=0.
  END DO
END DO

TRAD=THETA/180.*PI

IF (NREF.GT.0) THEN

  WRITE(6,'/'," Display reflector positions ? (Y/N)")
  READ(5,'(A)') ANS
  IF (ANS.EQ.'Y'.OR.ANS.EQ.'y') CALL DISP_REF_POS(ICHAN,OFFSET,TXT)

  WRITE(6,'/'," Display reflector coverage ? (Y/N)")
  READ(5,'(A)') ANS
  IF (ANS.EQ.'Y'.OR.ANS.EQ.'y') CALL DISP_REF_COV(ICHAN,OFFSET)

END IF

NREFOLD=NREF

WRITE(6,'/'," Reflector coords")
WRITE(6,'('," Position cursor, turn off cursor to stop")
READ(5,'*')
CALL RM_RCSP(ICHAN,IX0,IY0)                                IRam coords

DO WHILE (IX0.GE.0.)

  WRITE(6,'/'," Reflector bearing")
  WRITE(6,'('," Position cursor")
  READ(5,'*')
  CALL RM_RCSP(ICHAN,IX1,IY1)

  WRITE(6,'/'," Calculate coverage ? (Y/N)")
  READ(5,'(A)') ANS
  IF (ANS.EQ.'Y'.OR.ANS.EQ.'y') THEN
    CALL REF_COV(ICHAN,IX0,IY0,IX1,IY1,BEARING,K,TRAD)
  END IF

  HT_TER=MAP(IY0,IX0)
  IF (HT_TER.EQ.1.) HT_TER=0.
  WRITE(6,'/'," Terrain elevation at ('",I5,
&      " ",I5,") = ",I5," metres") IX0,IY0,
&      ININT(HT_TER)

  NREF=NREF+1
  REF(NREF,1)=IX0
  REF(NREF,2)=IY0
  IF (BEARING.LT.0.) BEARING=BEARING+360.
  REF(NREF,3)=BEARING
  REF(NREF,4)=BEARING-THETA
  IF (REF(NREF,4).LT.0.)
&      REF(NREF,4)=REF(NREF,4)+360.
  REF(NREF,5)=BEARING+THETA
  IF (REF(NREF,5).GT.360.)
&      REF(NREF,5)=REF(NREF,5)-360.

  DO I=1, 6

```

```

      REF(NREF,I+8)=K(I)          IStore ray endpts
    END DO

    CALL REF_HT(ICHAN,IX0,IY0,K(3),K(4),K(1),K(2),K(5),K(6),HT_TER)

    WRITE(6,'(///," Add reflectors to list ? (Y/N)"))
    READ(5,'(A)') ANS
    IF (ANS.EQ.'Y'.OR.ANS.EQ.'y') THEN
      NREFOLD=NREF
    ELSE
      DO J=1, 14
        REF(NREF,J)=0.
      END DO
      NREF=NREFOLD
    END IF

    WRITE(6,'(///," Reflector coords")')
    WRITE(6,'(
&   " Position cursor, turn off cursor to stop")')
    READ(5,'')
    CALL RM_RCSP(ICHAN,IX0,IY0)          IRam coords

  END DO

  IF (NREF.NE.0.) THEN

    WRITE(6,'("1"," No. of reflectors =",I3,
&   " Reflector beamwidth =",F5.1)') NREF,2.*THETA

    WRITE(6,'(///," REFLECTOR",8X,"COORDS (E,N)",
&   8X,"BEARING",5X,"ANGLE COVERAGE")')

    DO I=1, NREF
      WRITE(6,'(4X,I2,8X,F7.1,4X,F7.1,7X,F5.1,6X,F5.1,4X,F5.1)')
&   I,(REF(I,J),J=1,5)
    END DO

    WRITE(6,'(///," Write reflector information to file ? (Y/N)"))
    READ(5,'(A)') ANS
    IF (ANS.EQ.'Y'.OR.ANS.EQ.'y') THEN
      WRITE(6,'(///," Output file")')
      READ(5,'(A)') FNAME
      OPEN(1,FILE=FNAME,STATUS='NEW',ACCESS='SEQUENTIAL')
      WRITE(1,*) NREF,THETA,SCALE_FAC
      DO I=1, NREF
        WRITE(1,*) (REF(I,J),J=1,14)
      END DO
      CLOSE(1)
    END IF

  END IF

  RETURN
END

```

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NAME: SUBROUTINE REF COV

PURPOSE:
Display coverage area of reflector

CALL: CALL REF COV(ICHAN,IX0,IY0,IX1,IY1,BEARING,K,TRAD)

WHERE:

ICHAN	- Logical channel number
IX0	- x coord of reflector
IY0	- y coord of reflector (ram)
IX1	- x coord of point along reflector bearing line
IY1	- y coord of point along reflector bearing line (ram)
BEARING	- Bearing angle of reflector (deg)
K	- Integer array for vector endpoints (6)
TRAD	- Reflector half-beamwidth (rad)

```

SUBROUTINE REF COV(ICHAN,IX0,IY0,IX1,IY1,BEARING,K,TRAD)
IMPLICIT INTEGER*2 (I-N)
REAL B(3),RX,RY
INTEGER*2 XMINRAM,YMINRAM,XMAXRAM,YMAXRAM,K(6)
COMMON /BLK2/ XMINRAM,YMINRAM,XMAXRAM,YMAXRAM
COMMON /BLK5/ PI,PI2

```

```

IY0=YMAXRAM-IY0
IY1=YMAXRAM-IY1
DELX=IX1-IX0
DELY=IY1-IY0

```

```
IF (DELX.EQ.0. .AND. DELY.EQ.0.) THEN
  WRITE(6,'//," *** INVALID POINTS ****")'
  IY0=YMAXRAM-IY0
  RETURN
```

```
ELSE
  BEARING=ATAN2D(DELY,DELX)
  B(2)=ATAN2(DELY,DELX)
  B(1)=B(2)-TRAD
  IF(B(1).LT.*PI) B(1)=B(1)+2.*PI
  B(3)=B(2)+TRAD
  IF(B(3).GT.PI) B(3)=B(3)-2.*PI
```

END IF

DO I=1, 3

```
ANGLE=B(I)
TANG=TAN(ANGLE)
```

RX=-1.
RY=-1.

```
IF (ANGLE.EQ.0.) THEN
  IX=XMAXRAM
```

```

        IY=IY0
ELSE IF (ABS(ANGLE).EQ.PI) THEN
    IX=XMINRAM
    IY=IY0
ELSE IF (ANGLE.EQ.PI2) THEN
    IX=IX0
    IY=YMAXRAM
ELSE IF (ANGLE.EQ.-PI2) THEN
    IX=IX0
    IY=YMINRAM
ELSE IF (0..LT.ANGLE .AND. ANGLE.LT.PI2) THEN
    RX=XMAXRAM
    RY=TANG*(XMAXRAM-IX0)+IY0
    IF (RY.GT.FLOATI(YMAXRAM)) THEN
        RX=(YMAXRAM-IY0)/TANG+IX0
        RY=YMAXRAM
    END IF
ELSE IF (PI2.LT.ANGLE .AND. ANGLE.LT.PI) THEN
    RX=XMINRAM
    RY=-TANG*IX0+IY0
    IF (RY.GT.FLOATI(YMAXRAM)) THEN
        RX=(YMAXRAM-IY0)/TANG+IX0
        RY=YMAXRAM
    END IF
ELSE IF (-PI.LT.ANGLE .AND. ANGLE.LT.-PI2) THEN
    RX=XMINRAM
    RY=-TANG*IX0+IY0
    IF (RY.LT.0.) THEN
        RX=-IY0/TANG+IX0
        RY=YMINRAM
    END IF
ELSE IF (-PI2.LT.ANGLE .AND. ANGLE.LT.0.) THEN
    RX=XMAXRAM
    RY=TANG*(XMAXRAM-IX0)+IY0
    IF (RY.LT.0.) THEN
        RX=-IY0/TANG+IX0
        RY=YMINRAM
    END IF
END IF
IF (RX.GE.0. .OR. RY.GE.0.) THEN
    IF (RX.GE.FLOATI(XMAXRAM)) THEN
        IX=XMAXRAM
    ELSE
        IX=ININT(RX)
    END IF
    IF (RY.GE.FLOATI(YMAXRAM)) THEN
        IY=YMAXRAM
    ELSE
        IY=ININT(RY)
    END IF

```



```

END IF
      IY=YMAXRAM-IY
      CALL RM_WVU(ICHAN,IX0,YMAXRAM-IY0,IX,IY,1024)  IDisplay coverage
      K(2*I-1)=IX
      K(2*I)=IY
      IStore endpoints for
      Iregeneration of vectors
END DO
      IY0=YMAXRAM-IY0
      ICartesian to ramtek
RETURN
END

```

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NAME: SUBROUTINE REF HT

PURPOSE:
Find reflector height(s) at reflector site (IX0,IY0)

CALL REF HT(ICHAN,IX0,IY0,K(3),K(4),K(1),K(2),K(5),K(6),HT_TER)

WHERE:

- ICHAN - Logical channel number
- IX0 - Ramtek x coord of reflector site
- IY0 - Ramtek y coord of reflector site
- K(3) - Reflector coverage ray 1 endpoint, x (bearing)
- K(4) - Reflector coverage ray 1 endpoint, y (bearing)
- K(1) - Reflector coverage ray 2 endpoint, x (bearing-theta)
- K(2) - Reflector coverage ray 2 endpoint, y (bearing-theta)
- K(5) - Reflector coverage ray 3 endpoint, x (bearing+theta)
- K(6) - Reflector coverage ray 3 endpoint, y (bearing+theta)
- HT TER - Height of terrain at reflector site

```

SUBROUTINE REF_HT(ICHAN,IX0,IY0,KX1,KY1,KX2,KY2,KX3,KY3,HT_TER)
IMPLICIT INTEGER*2 (I-N)
REAL REF(20,14),HT(20)
INTEGER*2 TRACK(20,4),N(20),PF_FLAG
CHARACTER ANS*1
COMMON /BLK3/ TRACK,NTRK
COMMON /BLK4/ REF,NREF,THETA,SCALE_FAC
COMMON /BLK5/ PI,PI2
COMMON /BLK7/ WLAHGT

```

CON=4.*AHGT/WL

```
WRITE(6,(/," Reflector positioning in elevation",/,
& " Track section to evaluate (0 - stop)"))
READ(5,*) NUM
```

DO WHILE (NUM.NE.0)

```
WRITE(6,'(//," Manual mode ? (Y/N)"))
READ(5,'(A)') ANS
IF (ANS.EQ.'Y'.OR.ANS.EQ.'y') THEN
  WRITE(6,'(//," Position cursor for range1")')
  READ(5,*)
  CALL RM_RCSP(ICHAN,NX,NY)
  X12=FLOATI(NX)
  Y12=FLOATI(NY)
  WRITE(6,'(//," Position cursor for range2")')
  READ(5,*)
  CALL RM_RCSP(ICHAN,NX,NY)
  X13=FLOATI(NX)
  Y13=FLOATI(NY)
  WRITE(6,'(//," Position cursor for range3")')
  READ(5,*)
```

```

CALL RM_RCSP(ICHAN,NX,NY)
X14=FLOATI(NX)
Y14=FLOATI(NY)
ELSE
CALL LINE_EQUATION(TRACK(NUM,1),TRACK(NUM,2),TRACK(NUM,3),
& TRACK(NUM,4),XL1,YL1,SL1,BL1)
CALL LINE_EQUATION(IX0,IY0,KX1,KY1,XL2,YL2,SL2,BL2)
CALL LINE_EQUATION(IX0,IY0,KX2,KY2,XL3,YL3,SL3,BL3)
CALL LINE_EQUATION(IX0,IY0,KX3,KY3,XL4,YL4,SL4,BL4)

CALL LINE_INTERSECT(XL1,YL1,SL1,BL1,XL2,YL2,SL2,BL2,X12,Y12)
CALL LINE_INTERSECT(XL1,YL1,SL1,BL1,XL3,YL3,SL3,BL3,X13,Y13)
CALL LINE_INTERSECT(XL1,YL1,SL1,BL1,XL4,YL4,SL4,BL4,X14,Y14)
END IF

RANGE1=SQRT((X12-IX0)**2+(Y12-IY0)**2)*SCALE_FAC
RANGE2=SQRT((X13-IX0)**2+(Y13-IY0)**2)*SCALE_FAC
RANGE3=SQRT((X14-IX0)**2+(Y14-IY0)**2)*SCALE_FAC

WRITE(6,'//,
& " Range of reflector to track along bearing =",F9.2,
& " m")' RANGE1
WRITE(6,'//,
& " Range of reflector to track along bearing-theta =",F9.2,
& " m")' RANGE2
WRITE(6,'//,
& " Range of reflector to track along bearing+theta =",F9.2,
& " m")' RANGE3

WRITE(6,'//," Change terrain elevation, ranges ? (Y/N)"')
READ(5,'(A)') ANS
IF (ANS.EQ.'Y'.OR.ANS.EQ.'y') THEN
& WRITE(6,'//,
& " Input terrain elevation, range1, range2, range3"')
READ(5,*) HT_TER,RANGE1,RANGE2,RANGE3
END IF

WK1=CON/RANGE1
WK2=2.*PI*AHGT/WL
NN=ININT((WK1*(HT_TER+2.)-1.)/2.+5)
DO I=1, 10
N(I)=NN
HT(I)=(2.*NN+1.)/WK1
NN=NN+1
END DO

WRITE(6,'//," ***** Terrain elevation =",F7.2," m",/,
& " Possible N values and corresponding reflector heights (m)"')
& HT_TER
WRITE(6,'//," N :",10I7)' (N(I),I=1,10)
WRITE(6,'//," Ht :",10F7.2)' (HT(I),I=1,10)
WRITE(6,'//," Select reflector height"')
READ(5,*) REF(NREF,6)

R_START=RANGE1
IF (ABS(RANGE1-RANGE2).GT.ABS(RANGE1-RANGE3)) THEN
R_END1=RANGE2
R_END2=RANGE3
ELSE

```

```

        R_END1=RANGE3
        R_END2=RANGE2
    END IF

    WK3=WK2*REF(NREF,6)

    IF (R_START.LT.R_END1) THEN
        RINC=.1
    ELSE
        RINC=-.1
    END IF

    DO WHILE ((R_START.LE.R_END1 .AND. RINC.GT.0.)
&      .OR. (R_START.GE.R_END1 .AND. RINC.LT.0.))

        PROP_FAC=(SIN(WK3/R_START))**4

        IF (PROP_FAC.GT..9) THEN
            PROP_FAC_OLD=PROP_FAC
            PF_FLAG=0
        END IF

        IF (PROP_FAC_OLD.GT.PROP_FAC) THEN
            PROP_FAC_OLD=PROP_FAC
        ELSE IF (PROP_FAC_OLD.LT.PROP_FAC .AND. PF_FLAG.EQ.0) THEN
            CALL REFHT(R_START,PROP_FAC_OLD,CON,WK2)
            PF_FLAG=1
        END IF

        R_START=R_START+RINC

    END DO

    WK4=WK2*REF(NREF,7)
    R_START=RANGE1

    IF (R_START.LT.R_END2) THEN
        RINC=.1
    ELSE
        RINC=-.1
    END IF

    OPEN(7,ACCESS='SEQUENTIAL',STATUS='NEW')
    DO WHILE ((R_START.LE.R_END2 .AND. RINC.GT.0.)
&      .OR. (R_START.GE.R_END2 .AND. RINC.LT.0.))

&      PROP_FAC=(SIN(WK3/R_START))**4+(SIN(WK4/R_START))**4+
        (SIN(WK2*REF(NREF,8)/R_START))**4

        IF (PROP_FAC.LT..1) THEN
            WRITE(7,*) R_START,PROP_FAC
            CALL REFHT(R_START,PROP_FAC_OLD,CON,WK2)
        END IF

        R_START=R_START+RINC

    END DO
    CLOSE(7)

```

```

      WRITE(6,'(///," *****",',
&      " Reflector heights (m) :",3F12.4,', " *****")')
&      (REF(NREF,I),I=6,8)

      WRITE(6,'(///," Reflector positioning in elevation",',
&      " Track section to evaluate (0 - stop)")')
      READ(5,*) NUM

      END DO

      RETURN
      END

      SUBROUTINE REFHT(R,PF,CON,WK2)
      IMPLICIT INTEGER*2 (I-N)
      REAL REF(20,14)
      CHARACTER ANS*1
      COMMON /BLK4/ REF,NREF,THETA,SCALE_FAC

      WRITE(6,'(///," Range =",F9.2,10X,
&      " Propagation factor =",F7.4)") R,PF

      IF (REF(NREF,8).EQ.0.) THEN

        WRITE(6,'(///," Position another reflector ? (Y/N)")')
        READ(5,'(A)') ANS

        IF (ANS.EQ.'Y'.OR.ANS.EQ.'y') THEN

          IF (REF(NREF,7).EQ.0.) THEN
            K=7
            I2nd reflector
          ELSE
            K=8
            I3rd reflector
          END IF

          WRITE(6,'(///," Separation between reflectors ?")')
          READ(5,*) SEP

          WK=CON/R
          N=ININT((WK*(REF(NREF,K-1)+SEP)-1.)/2.+5)
          REF(NREF,K)=(2.*N+1.)/WK
          PF=(SIN(WK2*REF(NREF,K)/R))**4

          WRITE(6,'(///," ***** Reflector",I2)') K-5
          WRITE(6,'(///," Height =",F9.4,10X,
&      "Range =",F9.2,10X," Propagation factor =",F7.4)")
&      REF(NREF,K),R,PF
&

          END IF

        END IF

      RETURN
      END

      SUBROUTINE LINE_EQUATION(IX1,IY1,IX2,IY2,X,Y,S,B)
      IMPLICIT INTEGER*2 (I-N)

```

```
DELX=IX2-IX1
DELY=IY2-IY1
```

```
IF (DELY.EQ.0.) THEN
  Y=IY1
  S=0.
ELSE IF (DELX.EQ.0.) THEN
  X=IX1
  S=1.E6
ELSE
  S=DELY/DELX
  B=IY2-S*IX2
END IF
```

```
RETURN
END
```

```
SUBROUTINE LINE_INTERSECT(X1,Y1,S1,B1,X2,Y2,S2,B2,X,Y)
IMPLICIT INTEGER*2 (I-N)
```

```
IF (S1.NE.S2) THEN
  IF (S1.EQ.0.) THEN
    Y=Y1
    X=(Y-B2)/S2
  ELSE IF (S2.EQ.0.) THEN
    Y=Y2
    X=(Y-B1)/S1
  ELSE IF (S1.EQ.1.E6) THEN
    X=X1
    Y=S2*X+B2
  ELSE IF (S2.EQ.1.E6) THEN
    X=X2
    Y=S1*X+B1
  ELSE
    X=(B2-B1)/(S1-S2)
    Y=S1*X+B1
  END IF

```

```
ELSE
  WRITE(6,'(//," *****",/,
& " Slopes of track and coverage ray are the same -- parallel lines"
& ',," Intersection point set to (-1,-1)",
& ',," *****")')
  X=-1.
  Y=-1.

```

```
END IF
```

```
RETURN
END
```


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NAME:
SUBROUTINE DISP_REF_COV

PURPOSE:
Display reflector coverage

CALL:
CALL DISP_REF_COV(ICHAN,OFFSET)

WHERE:
ICHAN - Logical channel number
OFFSET - Data offset

SUBROUTINE DISP_REF_COV(ICHAN,OFFSET)
IMPLICIT INTEGER*2 (I-N)
REAL REF(20,14)
INTEGER*2 OFFSET
COMMON /BLK4/ REF,NREF,THETA,SCALE_FAC

CALL RM_EMP(ICHAN) Ierase overlay

DO I=1, NREF
IX0=REF(I,1)
IY0=REF(I,2)-OFFSET
DO J=9, 13, 2
IX1=REF(I,J)
IY1=REF(I,J+1)-OFFSET
CALL RM_WVU(ICHAN,IX0,IY0,IX1,IY1,1024)
END DO
END DO

RETURN
END

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NAME:
SUBROUTINE VIS_AZI

PURPOSE:
Find reflectors visible from test point (X0,Y0)
given reflector azimuth coverage patterns

CALL:
CALL VIS_AZI(X0,Y0)

WHERE:
X0 - Ramtek coord of vessel (col coord of array MAP)
Y0 - Ramtek coord of vessel (row coord of array MAP)

SUBROUTINE VIS_AZI(X0,Y0)
IMPLICIT INTEGER*2 (I-N)
REAL REF(20,14),BLRVIS(20)
INTEGER*2 LRVIS(20,2)
COMMON /BLK4/ REF,NREF,THETA,SCALE_FAC
COMMON /BLK6/ LRVIS,BLRVIS,NR

NR=0

DO J=1, 2
DO I=1, 20
LRVIS(I,J)=0
END DO
END DO

DO I=1, 20
BLRVIS(I)=0.
END DO

DO I=1, NREF

A1=REF(I,4) IReflector angle coverage
A2=REF(I,5)
ANGLE=ATAN2D(REF(I,2)-Y0,X0-REF(I,1)) ICartesian y

IF (A2.LT.A1) THEN IA2 - quadrant 1
A1=A1-360. IA1 - quadrant 4
ELSE
IF (ANGLE.LT.0.) ANGLE=ANGLE+360.
END IF

IF (ANGLE.GE.A1.AND.ANGLE.LE.A2) THEN
NR=NR+1
LRVIS(NR,1)=I IStore visible reflector #
BLRVIS(NR)=ANGLE IReflector-ship angle
END IF

END DO
RETURN
END

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NAME: SUBROUTINE VIS_HT

PURPOSE:
Find reflectors visible from test point (X0,Y0) given the terrain elevation, antenna and reflector heights; determine the presence/absence of multipath.

CALL: CALL VIS HT(X0,Y0)

WHERE:
X0 - Ramtek coord of vessel (col coord of array MAP)
Y0 - Ramtek coord of vessel (row coord of array MAP)

```

SUBROUTINE VIS HT(X0,Y0)
IMPLICIT INTEGER*2 (I-N)
REAL REF(20,14),BLRVIS(20),BIWK(20),MIN_COVERAGE
INTEGER*2 LRVIS(20,2),IWK(20,2),SITE
INTEGER*2 MAP(0:999,0:999)
COMMON /BLK1/ MAP
COMMON /BLK4/ REF,NREF,THETA,SCALE_FAC
COMMON /BLK6/ LRVIS,BLRVIS,NR
COMMON /BLK7/ WL,AHGT
COMMON /BLK8/ IWK,BIWK

```

 $L=0$

```
DO J=1, 2
  DO I=1, 20
    IWK(I,J)=0
  END DO
END DO
```

```
DO I=1, 20
    BIWK(I)=0.
END DO
```

$$\text{MIN\_COVERAGE} = \text{AHGT} / \text{TAND}(\text{THETA})$$

DO I=1, NR

SITE=LRVIS(I,1)	IReflector site #
RHGT=REF(SITE,6)	Iht of lowest reflector
X1=REF(SITE,1)	IReflector coords
Y1=REF(SITE,2)	
DELX=X1-X0	
DELY=Y1-Y0	IRamtek coords

```
IF (DELY.EQ.0.) THEN
  Y=Y0
  S=0.
ELSE IF (DELX.EQ.0.) THEN
  X=X0
```

```

      S=1.E6
ELSE
  S=DELY/DELX
  B=Y1-S*X1
END IF
                                     ISlope
                                     IIntercept

HT_DIFF=RHGT-AHGT
DIST=SQRT(DELX**2+DELY**2)
                                     IReflector-antenna ht diff
                                     IAntenna-reflector distance

IF (X1.GT.X0.AND.ABS(S).LE.1.) THEN  IFind start, end points for
  J=X0+1                             I test segment
  JE=X1-1
  JINC=1
  K=1
ELSE IF (X0.GT.X1.AND.ABS(S).LE.1.) THEN
  J=X0-1
  JE=X1+1
  JINC=-1
  K=2
ELSE IF (Y1.GT.Y0) THEN
  J=Y0+1
  JE=Y1-1
  JINC=1
  K=3
ELSE
  J=Y0-1
  JE=Y1+1
  JINC=-1
  K=4
END IF

S_LOS=ABS(HT_DIFF)/DIST
C1=AHGT*DIST
C2=AHGT+RHGT
                                     ISlope of LOS

LOS_FLAG=2
                                     I0 - no obstructions along LOS
                                     I1 - obstruction,
                                     I reflector not visible
                                     I2 - indeterminate

MPATH_FLAG=2
                                     I0 - no multipath
                                     I1 - multipath
                                     I2 - indeterminate

DO WHILE ( ( J.LE.JE.AND.JINC.EQ.1)  ICheck pts along LOS
&      .OR.(J.GE.JE.AND.JINC.EQ.-1) )
&      .AND. (LOS_FLAG.EQ.2) )

  IF (DELY.EQ.0.) THEN
    X=J
  ELSE IF (DELX.EQ.0.) THEN
    Y=J
  ELSE IF (ABS(S).GT.1.) THEN
    Y=J
    X=(Y-B)/S
  ELSE
    X=J
    Y=S*X+B
  END IF
    ICal test pt along LOS

```



```

INX=ININT(X)
INY=ININT(Y)
HT_TER=MAP(INY,INX)      !Ht of terrain at (X,Y)
IF (HT_TER.EQ.1.) HT_TER=0.

IF (HT_DIFF.NE.0.) THEN
  IF (HT_DIFF.GT.0.) THEN      !RHGT > AHGT
    HT_LOS=S_LOS*SQRT((X-X0)**2+(Y-Y0)**2)+AHGT
  ELSE
    !RHGT < AHGT
    HT_LOS=S_LOS*SQRT((X-X1)**2+(Y-Y1)**2)+RHGT
  END IF
ELSE
  HT_LOS=RHGT
END IF

IF (HT_TER.GE.HT_LOS) THEN      !Terrain ht > LOS
  LOS_FLAG=1
  !Terrain obstruction
  MPATH_FLAG=0
  !No multipath
  CALL WR1(X0,Y0,INX,INY,1,SITE)
END IF

IF (MPATH_FLAG.EQ.2) THEN

  RANGE1=SQRT((X-X0)**2+(Y-Y0)**2) !Ship-test pt rel distance
  TWORANGE1=2.*RANGE1
  IF (DIST.EQ.TWORANGE1) THEN      !Cal ht of reflection pt
    HT_RPT=1.E6
  ELSE
    HT_RPT=(C1-C2*RANGE1)/(DIST-TWORANGE1)
  END IF

  IF ( (HT_RPT.LT.RHGT)
    & .AND. (HT_RPT.LT.HT_LOS)
    & .AND. (RANGE1.GE.MIN_COVERAGE)
    & .AND. (HT_RPT.GE.HT_TER)
    & .AND. ((HT_RPT-HT_TER).LE.15.) ) THEN      !Valid refl pt

    XR=X
    YR=Y
    !Reflection pt coords

    IF (DELY.EQ.0.) THEN
      YY=YR
    ELSE IF (DELX.EQ.0.) THEN
      XX=XR
    END IF

    IF (K.EQ.1) THEN
      K=XR+1
    ELSE IF (K.EQ.2) THEN
      K=XR-1
    ELSE IF (K.EQ.3) THEN
      K=YR+1
    ELSE IF (K.EQ.4) THEN
      K=YR-1
    END IF

    RANGE2=DIST-RANGE1
    !Reflection pt-reflector
    ! relative distance

```

```

S_LOS_MPATH=(RHGT-HT_RPT)/RANGE2 ISlope of refl ray

DO WHILE ( ( (K.LE.JE.AND.JINC.EQ.1)
&          .OR.(K.GE.JE.AND.JINC.EQ.-1) )
&          .AND. (MPATH_FLAG.EQ.2) )

    IF (DELY.EQ.0.) THEN
        XX=K
    ELSE IF (DELY.EQ.0.) THEN
        YY=K
    ELSE IF (ABS(S).GT.1.) THEN
        YY=K
        XX=(YY-B)/S
    ELSE
        XX=K
        YY=S*XX+B
    END IF

    HT_TER_MPATH=MAP(ININT(YY),ININT(XX))
    IF (HT_TER_MPATH.EQ.1.) HT_TER_MPATH=0.
    HT_LOS_MPATH=S_LOS_MPATH*SQRT((XX-XR)**2
&          +(YY-YR)**2)+HT_RPT

    IF (HT_TER_MPATH.GE.HT_LOS_MPATH)
&      MPATH_FLAG=0      IExit loop

    K=K+JINC

END DO

IF (MPATH_FLAG.EQ.0) THEN      ITerrain obstruction,
    MPATH_FLAG=2              I reset flag,
                              I continue testing
ELSE IF (MPATH_FLAG.EQ.2) THEN INo obstruction,
    MPATH_FLAG=1              I multipath,
    LOS_FLAG=0                I LOS clear,
                              I no further testing
END IF

END IF

END IF

J=J+JINC

END DO

IF (LOS_FLAG.EQ.2) LOS_FLAG=0      INo obstruction, refl visible
IF (MPATH_FLAG.EQ.2) MPATH_FLAG=0  INo multipath

IF (LOS_FLAG.EQ.0) THEN
    L=L+1
    IWK(L,1)=SITE                IStore reflector site number
    IWK(L,2)=MPATH_FLAG
    IWK(L,2)=1
    BIWK(L)=BLRVIS(I)
END IF

```

END DO

NR=L

!Number of reflectors visible

DO I=1, 20

LRVIS(I,1)=IWK(I,1)

!Update visible reflector list

LRVIS(I,2)=IWK(I,2)

BLRVIS(I)=BIWK(I)

END DO

RETURN

END

SUBROUTINE WR1(X0,Y0,INX,INY,N,SITE)

IMPLICIT INTEGER*2 (I-N)

INTEGER*2 SITE

WRITE(6,(/," Vessel position (",
& I4," ",I4," ") ININT(X0),ININT(Y0)

IF (N.EQ.1) THEN

WRITE(6,(/" Test point (" ,I4," ",I4,
& ") Reflector not visible :",I3)' INX,INY,SITE

ELSE

WRITE(6,(/" Test point (" ,I4," ",I4,
& ") No multipath")' INX,INY

END IF

RETURN

END

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NAME: SUBROUTINE TRK POS

PURPOSE:
Check specified points along vessel track for reflector visibility

CALL: CALL TRK POS(ICHAN)

WHERE:
ICHAN - Logical channel number

```
SUBROUTINE TRK_POS(ICHAN)
IMPLICIT INTEGER*2 (I-N)
REAL BLRVIS(20)
INTEGER*2 LRVIS(20,2)
COMMON /BLK6/ LRVIS,BLRVIS,NR
COMMON /BLK7/ WLAHGT
```

```
WRITE(6,'//," Position cursor, turn off cursor to stop"')
READ(5,*)
CALL RM RCSP(ICHAN,IX0,IY0)
```

DO WHILE (IX0.GE.0)

CALL VIS AZI(FLOATI(IX0),FLOATI(IY0))

IF (NR.EQ.0) THEN

```
WRITE(6, '(//, " *** No reflectors visible ***")')
```

ELSE

```
WRITE(6,'//," Reflector site(s) visible in azimuth :")'
WRITE(6,*) (LRVIS(I,1),I=1,NR)
```

```
CALL VIS_HT(FLOAT(IX0),FLOAT(IY0),ichan)
WRITE(6,7//," Reflector site(s) unobstructed by terrain :")
WRITE(6,*) (LRVIS(I,1),I=1,NR)
```

```
DO I=1, NR
  WRITE(6,/, " Site", I3) LRVIS(I,1)
  IF (LRVIS(I,2).EQ.0) THEN
    WRITE(6,*) 'No multipath'
  ELSE
    WRITE(6,*) 'Multipath'
  END IF
END DO
```

END IF

```
WRITE(6,'//," Position cursor, turn off cursor to stop"')
READ(5,*)
```

CALL RM_RCSP(ICHAN,IX0,IY0)
END DO
RETURN
END

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NAME: SUBROUTINE DISP_TXT

PURPOSE:
Display numbering for vessel tracks
and reflector positions

CALL: CALL DISP_TXT(ICHAN,IVAL,ISIZE,IX,IY,I,TXT1)

WHERE:

- ICHAN - Logical channel number
- IVAL - Text intensity value
- ISIZE - Text size
- IX - X coord
- IY - Y coord
- I - # characters
- TXT1 - Text string

```

SUBROUTINE DISP TXT(ICHAN,IVAL,ISIZE,IX,IY,I,TXT1)
IMPLICIT INTEGER*2 (I-N)
INTEGER*2 WT(13)
CHARACTER TXT1*80,TXT2*80
EQUIVALENCE (TXT2,WT(13))

```

WT(1)='0C0B'X	IOP code+RP+OF1÷DF
WT(2)='84C1'X	IOF1:COP+SIZ+SCN+WIN+WMSK
WT(3)=IVAL	IWMSK
WT(4)=0	IX min
WT(5)=0	IY min
WT(6)=1279	IX max
WT(7)=1023	IY max
WT(8)=0	ISCN
WT(9)=ISIZE	ISIZ
WT(10)=IX	ICOP X
WT(11)=IY	ICOP Y
WT(12)=I	I# characters

```
DO J=1, 80
      TXT2(J:J)=TXT1(J:J)
END DO
```

CALL RMOUT(ICHAN,WT,(I+1)/2+12)

RETURN
END

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NAME:
SUBROUTINE DISP_ERR

PURPOSE:
Read error files and display on Ramtek

CALL:
CALL DISP_ERR(ICHAN,OFFSET,TXT)

WHERE:
ICHAN - Logical channel number
OFFSET - Data offset
TXT - Text string

```
SUBROUTINE DISP_ERR(ICHAN,OFFSET,TXT)
IMPLICIT INTEGER*2 (I-N)
REAL ERR(1250),EMIN(20),EMAX(20),EMEAN(20)
INTEGER*2 IX(1250),IY(1250),NOP(20),OFFSET
CHARACTER TXT*80,FNAME*20,ANS*1

IVAL=2048

WRITE(6,'(//," Read data file ? (Y/N)"))
READ(5,'(A)') ANS
IF (ANS.EQ.'Y'.OR.ANS.EQ.'y') THEN
  WRITE(6,'(//," Error file")')
  READ(5,'(A)') FNAME
  OPEN(3,FILE=FNAME,STATUS='OLD',ACCESS='SEQUENTIAL',
    & FORM='UNFORMATTED')
  I=1
  J=0
  READ(3) IX(1),IY(1),ERR(1)
  DO WHILE (IX(I).NE.-1 .AND. IY(I).NE.-1)
    IF (IX(I).EQ.0 .AND. IY(I).EQ.0) THEN
      J=J+1
      READ(3) NOP(J),EMIN(J),EMAX(J),EMEAN(J)
    END IF
    I=I+1
    READ(3) IX(I),IY(I),ERR(I)
  END DO
  CLOSE(3)
  NPTS=I-2
END IF

WRITE(6,'(//," Error threshold value")')
READ(5,'(*)') THVAL

I=1000-ININT(20.*THVAL)
CALL RM_WVU(ICHAN,20,700,20,1000,IVAL)
CALL RM_WVU(ICHAN,20,1000,1270,1000,IVAL)
CALL RM_WVU(ICHAN,20,1,1270,1,IVAL)

J=15
DO I=700, 1000, 20
```

```

      CALL RM_WVU(ICHAN,15,I,20,I,IVAL)
      WRITE(TXT(1:2),'(I2)' J
      CALL DISP_TXT(ICHAN,IVAL,0,0,I-4,2,TXT)
      J=J-1
END DO

I=21
J=1
DO WHILE (J.LE.NPTS .AND. I.LE.1279)
  IF (J.EQ.1) THEN
    ICNT=1
    CALL RM_WVU(ICHAN,I,1000,I,1009,IVAL)      ITick mark
    WRITE(TXT,'(I1)' ICNT
    CALL DISP_TXT(ICHAN,IVAL,0,I-2,1013,1,TXT)
    CALL RM_WVU(ICHAN,I,1000,I,1000-ININT(20.*ERR(J)),IVAL)
    I=I+1
  ELSE IF (IX(J).EQ.0.AND.IY(J).EQ.0) THEN
    ICNT=ICNT+1
    CALL RM_WVU(ICHAN,I,1000,I,1009,IVAL)      ITick mark
    WRITE(TXT,'(I1)' ICNT
    CALL DISP_TXT(ICHAN,IVAL,0,I-2,1013,1,TXT)
  ELSE
    CALL RM_WVU(ICHAN,I,1000,I,1000-ININT(20.*ERR(J)),IVAL)
    I=I+1
  END IF
  IF (ERR(J).GE.THVAL) THEN
    K=IX(J)
    L=IY(J)-OFFSET
    CALL RM_WVU(ICHAN,K,L,K,L,IVAL)
  END IF
  J=J+1
END DO

K=1010
L=10
TXT='ERROR IN METERS'
CALL DISP_TXT(ICHAN,2048,'0101'X,K,L,15,TXT)

DO I=1, ICNT
  K=1010
  L=L+60
  TXT='TRACK '
  TXT(7:7)=CHAR(I+48)
  CALL DISP_TXT(ICHAN,IVAL,'0101'X,K,L,7,TXT)
  L=L+20
  WRITE(TXT(1:3),'(I3)' NOP(I)
  TXT(4:10)=' POINTS'
  CALL DISP_TXT(ICHAN,IVAL,'0101'X,K,L,10,TXT)
  L=L+20
  TXT='MIN = '
  WRITE(TXT(8:15),'(G8.3)' EMIN(I)
  CALL DISP_TXT(ICHAN,IVAL,'0101'X,K,L,15,TXT)
  L=L+20
  TXT='MAX = '
  WRITE(TXT(8:15),'(G8.3)' EMAX(I)
  CALL DISP_TXT(ICHAN,IVAL,'0101'X,K,L,15,TXT)
  L=L+20
  TXT='MEAN = '
  WRITE(TXT(8:15),'(G8.3)' EMEAN(I)

```

CALL DISP_TXT(ICHAN,IVAL,'0101'X,K,L,15,TXT)
END DO

RETURN
END

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NAME: SUBROUTINE RM_EMP

PURPOSE:
Erase memory plane(s)

CALL: CALL RM_EMP(ICHAN)

WHERE:
ICHAN - Logical channel number

```

SUBROUTINE RM_EMP(ICHAN)
IMPLICIT INTEGER*2 (I-N)
INTEGER*2 MP(12),BERS(3)

```

```
BERS(1)='2B02'X
BERS(2)=1
BERS(3)=0
```

IOP code + OF1
IOF1: WMSK - write mask
IWMSK

```
WRITE(6,('/'," # planes to erase"))
READ(5,*) N
```

IF (N.NE.0) THEN

```
WRITE(6,/, " Memory plane(s), 0-11, ",
& "bits 10 and 11 are overlay planes")
READ(5,*) (MP(I),I=1,N)
```

DO I=1, N

```

BERS(3)=BERS(3)+2**MP(I)
END DO

```

ISet memory bits

CALL RMOUT(ICHAN,BERS,3)

END IF

RETURN
END

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NAME: SUBROUTINE RM_BERS

PURPOSE:
Clear memory planes (bulk erase)

CALL: CALL RM_BERS(ICHAN)

WHERE:
ICHAN - Logical channel number

```
SUBROUTINE RM_BERS(ICHAN)
  IMPLICIT INTEGER*2 (A-Z)
  INTEGER*2 BERS(3)
```

```
BERS(1)='2B02'X
BERS(2)=1
BERS(3)='FFFF'X
```

IOP code + OF1
IOF1: WMSK
IWMSK

CALL RMOUT(ICHAN,BERS,3)

!Clear memory planes

RETURN
END

C
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C

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NAME:
PROGRAM SIM

PURPOSE:
Simulate and collect statistics on
reflector geometry

PROGRAM SIM
IMPLICIT INTEGER*2 (I-N)
REAL BLRVIS(20),AZBP(40),ELBP(40)
INTEGER*2 TRACK(20,4),LRVIS(20,2)
COMMON /BLK3/ TRACK,NTRK
COMMON /BLK6/ LRVIS,BLRVIS,NR
COMMON /BLKE/ AZBP,ELBP,TGTTEL,HEADING
COMMON /BLKG/ DPS
COMMON /BLKH/ NOP,NOPTOTAL
COMMON /BLKI/ ERP,ERRTOTAL,EMAX,EMIN,NX1,NY1,NX2,NY2

NOPTOTAL=0
ERRTOTAL=0.

CALL RDWI(ICHAN,OFFSET)

CALL PMT

DO I=1, NTRK

NOP=0
NX1=0
NY1=0
NX2=0
NY2=0
ERR=0.
EMAX=0.
EMIN=1000.

WRITE(2,('"1"'))
WRITE(2,('" Track ",I3)') I

DELX=TRACK(I,3)-TRACK(I,1)
ADELX=ABS(DELX)
DELY=TRACK(I,4)-TRACK(I,2)
ADELY=ABS(DELY)

HEADING=ATAN2D(-DELY,DELX)
IF (HEADING.LT.0.) HEADING=HEADING+360.

IF (DELY.EQ.0.) THEN

ABSS=0.
PHI=0.

ELSE IF (DELX.EQ.0.) THEN

ABSS=1.E6
PHI=1.570796327

IPI/2

ELSE


```

      ABSS=ADELY/ADELX
      PHI=ATAN(ABSS)
END IF

IF (DELX.NE.0.) XSIGN=DELX/ADELX
IF (DELY.NE.0.) YSIGN=DELY/ADELY

IF (DPS.EQ.0.) THEN                                IPixel mode
  IF (ABSS.LE.1.) THEN
    XINC=XSIGN
    YINC=SIN(PHI)/COS(PHI)*YSIGN
  ELSE
    XINC=COS(PHI)/SIN(PHI)*XSIGN
    YINC=YSIGN
  END IF
ELSE
  XINC=DPS*COS(PHI)*XSIGN
  YINC=DPS*SIN(PHI)*YSIGN
END IF

X=TRACK(I,1)
Y=TRACK(I,2)

DO WHILE (ABS(X-TRACK(I,1)).LE.ADELX                ICheck pts along vessel
  & .AND. ABS(Y-TRACK(I,2)).LE.ADELY                I track

    CALL VIS_AZI(X,Y)

    IF (NR.GE.1) THEN
      CALL VIS_HT(X,Y)

      IF (NR.GE.1) THEN
        CALL DETECTION(X,Y)

        IF (NR.GE.0) THEN
          CALL PREC(X,Y)
        ELSE
          & WRITE(2, '//, " Test point : (" ,I4, ", ",I4,
          & " )") ININT(X),ININT(Y)
          & WRITE(2, '(
          & " Reflector(s) visible : ",2I4)')
          & (LRVIS(K,1),K=1,NR)
          & WRITE(2, '(' " Subroutine PREC not executed" ')')
          END IF

        ELSE
          & WRITE(2, '//, " Test point : (" ,I4, ", ",I4,
          & " )") ININT(X),ININT(Y)
          & WRITE(2, '(
          & " Reflector(s) visible : ",2I4)')
          & (LRVIS(K,1),K=1,NR)
          & WRITE(2, '(' " Subroutines DETECTION, PREC not executed" ')')
          END IF

        ELSE
          & WRITE(2, '//, " Test point : (" ,I4, ", ",I4,
          & " )") ININT(X),ININT(Y)
          & WRITE(2, '(

```

```

&      " Reflector(s) visible : ",2I4)' (LRVIS(K,1),K=1,NR)
      WRITE(2,('
&      " Subroutines VIS_HT, DETECTION, PREC not executed"))
      END IF

      X=X+XINC      ICal test pt along track
      Y=Y+YINC

      END DO

      EMEAN=ERR/NOP
      WRITE(2,('///," Number of points evaluated =",I5)' NOP
      WRITE(2,('///," Mean error =",F7.2," meters')' EMEAN
      WRITE(2,('///," Maximum error =",F7.2," meters at ("
&      I4," ",I4," ")' EMAX,NX1,NY1
      WRITE(2,('///," Minimum error =",F7.2," meters at ("
&      I4," ",I4," ")' EMIN,NX2,NY2

      X=0.
      WRITE(3) ININT(X),ININT(X),X      IEnd of track
      WRITE(3) NOP,EMIN,EMAX,EMEAN

      END DO

      WRITE(2,('"1", " Number of tracks evaluated =",I4)' NTRK
      WRITE(2,('///," Total number of points evaluated =",I6)' NOPTOTAL
      WRITE(2,('///," Mean error =",F7.2," meters')' ERRTOTAL/NOPTOTAL

      CLOSE(2)
      I=-1
      X=-1.
      WRITE(3) I,I,X      IEnd of data
      CLOSE(3)

      STOP
      END

```



```

READ(5,*) PCON,RCON,DPS
WRITE(6,'/'," Max pitch, roll angle (deg)"))
READ(5,*) PAM, RAM

WRITE(6,'///'," RADAR PARAMETERS")
WRITE(6,'/'," Transmitter power (W), frequency (GHz), PRF")
READ(5,*) PT,WL,IPT

WRITE(6,'///'," ANTENNA PARAMETERS")
WRITE(6,'/'," Gain (dB), RPM, height above sea level (m)"))
READ(5,*) G0,SPD,AHGT
WRITE(6,'/'," Azimuth, elevation beamwidth (deg)"))
READ(5,*) AZBW,ELBW

WRITE(6,'///'," REFLECTOR PARAMETERS")
WRITE(6,'/'," Reflector file name")
READ(5,'(A)') FN_REF
WRITE(6,'/'," Reflector edge length (m)"))
READ(5,*) RCS

WRITE(6,'///'," RANGE MEASUREMENT PARAMETERS")
WRITE(6,'/'," Range error (m)"))
READ(5,*) THVAL(1)
WRITE(6,'/'," Zero range mark error (m)"))
READ(5,*) THVAL(2)
WRITE(6,'/'," Uncertainty in reflector coords (m)"))
READ(5,*) THVAL(3)
WRITE(6,'/'," Uncertainty in propagation velocity (ppm)"))
READ(5,*) SIG1

WRITE(6,'///'," Create parameter file ? (Y/N)"))
READ(5,'(A)') ANS

IF (ANS.EQ.'Y'.OR.ANS.EQ.'y') THEN

    WRITE(6,'/'," Parameter file name (output)"))
    READ(5,'(A)') FN_DAT

    OPEN(1,FILE=FN_DAT,STATUS='NEW',ACCESS='SEQUENTIAL')
    WRITE(1,'(A)') FN_VES,FN_REF
    WRITE(1,*) SEED,PCON,RCON,DPS
    WRITE(1,*) PAM, RAM,PT,WL,IPT
    WRITE(1,*) G0,SPD,AHGT
    WRITE(1,*) AZBW,ELBW,RCS
    WRITE(1,*) (THVAL(I),I=1,3),SIG1
    CLOSE(1)

END IF

END IF

OPEN(1,FILE=FN_VES,STATUS='OLD',ACCESS='SEQUENTIAL')
READ(1,*) NTRK                                     !# of vessel tracks
DO I=1, NTRK
    READ(1,*) (TRACK(I,J),J=1,4)                   !Vessel track endpts.
END DO
CLOSE(1)

OPEN(1,FILE=FN_REF,STATUS='OLD',ACCESS='SEQUENTIAL')

```

```

READ(1,*) NREF,THETA,SCALE_FAC
DO I=1, NREF
  READ(1,*) (REF(I,J),J=1,14)
END DO
CLOSE(1)

WRITE(6,'///," Stats file"')
READ(5,'(A)') FN_DAT
OPEN(2,FILE=FN_DAT,STATUS='NEW',ACCESS='SEQUENTIAL')

WRITE(6,'(," Position error file for Ramtek"')
READ(5,'(A)') FN_DAT

OPEN(3,FILE=FN_DAT,STATUS='NEW',ACCESS='SEQUENTIAL',FORM='UNFORMATTED')

WRITE(2,'(," Vessel track file : ",A20)') FN_VES
WRITE(2,'(///," Reflector file : ",A20)') FN_REF
WRITE(2,'(///," Seed for random number generator : ",I10)') SEED

WRITE(2,'(///," Pitch period : ",F6.2," s",8X,
& "Roll period : ",F6.2," s",8X,
& "Ship speed : ",F6.2," m/s")') PCON,RCON,DPS

WRITE(2,'(," Maximum pitch angle : ",F6.2," deg",8X,
& "Maximum roll angle : ",F6.2," deg")') PAM,RAM

WRITE(2,'(///," Transmitter power : ",I6," W",8X,
& "Frequency : ",F6.2," GHz",8X,
& "PRF : ",I5,"/s")') ININT(PT),WL,ININT(IPT)

WRITE(2,'(///," Antenna gain : ",F6.2," dB",8X,
& "RPM : ",I3,8X,
& "Height above sea level : ",F6.2," m")') G0,ININT(SPD),AHGT

WRITE(2,'(," Azimuth beamwidth : ",F6.2," deg",8X,
& "Elevation beamwidth : ",F6.2," deg")') AZBW,ELBW

WRITE(2,'(///," Reflector edge length : ",F6.2," m")') RCS

WRITE(2,'(///," Noise and instrument errors : ",F6.2," m")') THVAL(1)
WRITE(2,'(," Uncertainty in zero range mark : ",F6.2," m")') THVAL(2)
WRITE(2,'(," Uncertainty in reflector coords : ",F6.2," m")') THVAL(3)
WRITE(2,'(," Uncertainty in propagation velocity : ",I3," ppm")')
& ININT(SIG1)

WRITE(2,'("1",
& " Site      Coords (X,Y)      Bearing      Reflector Heights"
& )')
DO I=1, NREF
  WRITE(2,'(2X,I2,7X,"(",I4,"",I4,"")",7X,F6.2,
& 2X,3F8.2)') I,ININT(REF(I,1)),ININT(REF(I,2)),
& REF(I,3),(REF(I,J),J=6,8)
END DO

WRITE(2,'(///," Track      Start coords      End coords")')
DO I=1, NTRK
  WRITE(2,'(2X,I2,7X,"(",I4,"",I4,"")",7X,

```

```

&      "(,14,,14,)" I,(TRACK(I,J),J=1,4)
END DO

PTIME=RAN(SEED)*PCON          IInit value for pitch generator
RTIME=RAN(SEED)*RCON          IInit value for roll generator

PCON=2.*PI/PCON               I2*pi/pitch_period for subr PRR
RCON=2.*PI/RCON               I2*pi/roll_period for subr PRR

WL=.3/WL                      IWavelength (m)
IPT=1./IPT                    IInterpulse time

IF (DPS.NE.0.) THEN
  DPS=DPS*60./SPD              IDistance travelled/scan (m/s)
                                I speed*60/RPM
  DPS=DPS/SCALE_FAC           IReduce to Ramtek screen
END IF                          I distance

SPD=60./SPD/360.              ITime to scan 1 degree
                                I (60/RPM)/360 degrees
NPULSES=ININT(SPD*AZBW/IPT)   I# pulses as antenna scans
                                I across reflector
IPA=IPT/SPD                   IInterpulse angle

ACON=2.78/AZBW**2             IAzimuth beam pattern const
ECON=2.78/ELBW**2             IElevation beam pattern const

SIG=THVAL(1)**2+THVAL(2)**2+THVAL(3)**2
SIG1=SIG1*1.E-6

REFAC=PT*WL*WL/(4.*PI)**3     IRadar equation factor
                                I subr DETECTION

G0=10.**(G0/10.)
RCS=((4.*PI/3./WL*WL)*RCS**4)*.8 IReflector radar cross section
VAL=REFAC*G0*G0*RCS
RANGE=120.

DO I=1, 32                     IThreshold values for detection
  RANGE=RANGE+360.             I480 m - 11640 m, 32 levels
  THVAL(I)=ALOG10(VAL/RANGE**4)-.3 IThreshold = PR - 3 dB
END DO

PFAC=2.*PI*AHGT/WL            ISubr DETECTION

RETURN
END

```


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PURPOSE: Calculate pitch and roll angles corresponding to ship position at time of pulse transmission; assume simple harmonic motion for pitch and roll

WHERE:
NPULSES - number of pulses as antenna scans across
reflector (SPD * azimuth beamwidth * prf)

```

SUBROUTINE PRR(NPULSES)
IMPLICIT INTEGER*2 (I-N)
REAL PITCH(40),ROLL(40),IPT
COMMON /BLKA/ PTIME,RTIME,PCON,RCON,PAM,RAM,IPT
COMMON /BLKD/ PITCH,ROLL

```

DO I=1, NPULSES

PITCH(I)=SIN(PCON*PTIME)*PAM	!Generate pitch angles
ROLL(I)=SIN(RCON*RTIME)*RAM	!Generate roll angles

```
PTIME=PTIME+IPT           !Update time value
RTIME=RTIME+IPT
```

END DO

RETURN
END

n n n n n n n n n n n n n n n n

SUBROUTINE BMPN

Modify antenna beam patterns in azimuth and elevation due to the effects of pitch and roll motions of vessel, and rotation angle of antenna relative to ship bearing; assume gaussian beam shape in azimuth and elevation

CALL BMPN(X0,Y0,XR,YR,RR,NPULSES,IPA)

X0,Y0 - vessel coords
 XR,YR - reflector coords
 RR - range in meters
 NPULSES - number of pulses as antenna scans
 across reflector
 IPA - interpulse angle

DO I=1, 40

ELBP(I)=0.

Antenna azi half beamwidth
Antenna ele half beamwidth

IShip-reflector angle in deg

! antenna direction

IBeam centre (antenna dir), deg

!Beam centre z coord

!Antenna dir-ship heading angle

|Beam centre x coord

! y coord

!Sin(pitch)

 $\cos(\text{pitch})$ $-\sin(\text{roll})$

```

CR=COSD(ROLL(I))
SRO=SIND(ROT)
CRO=COSD(ROT)

A1=CRO*X-SRO*Y
A2=SRO*X+CRO*Y
A3=SP*A1
A4=A3-CP*Z

XP=CP*A1+SP*Z
YP=SR*A4+CR*A2
ZP=SR*A2-CR*A4

CON=ATAN2D(YP,XP)
IF (CON.LT.0.) CON=CON+360.
CON=ABS(CON-THETA1)
IF (CON.LT.AZBW2) AZBP(I)=EXP(-ACON*CON**2)

CON=ABS(ATAN2D(ZP,RR)-TGTEL)
IF (CON.LT.ELBW2) ELBP(I)=EXP(-ECON*CON**2)

GAM=GAM+IPA

END DO
C   write(6,*) '*** AZBP ***', (azbp(i),i=1,npulses)
C   write(6,*) '*** ELBP ***', (elbp(i),i=1,npulses)
RETURN
END

```

ICos(roll)
ISin(rotation)
ICos(rotation)

IModified beam centre x coord
I y coord
I z coord

Angle from beam centre

Angle from beam centre

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NAME: SUBROUTINE DETECTION

PURPOSE: Find reflectors visible from test point (X0,Y0) taking into account the ship's motion, multiple hits/target, multipath and echo signal power

CALL: CALL DETECTION(X0,Y0)

WHERE:
X0 - Ramtek coord of vessel (col coord of array MAP)
Y0 - Ramtek coord of vessel (row coord of array MAP)

```

SUBROUTINE DETECTION(X0,Y0)
IMPLICIT INTEGER*2 (I-N)
REAL REF(20,14),BLRVIS(20),BIWK(20),THVAL(32),AZBP(40),ELBP(40),IPT,IPA
INTEGER*2 LRVIS(20,2),IWK(20,2),SITE
COMMON /BLK4/ REF,NREF,THETA,SCALE_FAC
COMMON /BLK6/ LRVIS,BLRVIS,NR
COMMON /BLK7/ WL,AHGT
COMMON /BLK8/ IWK,BIWK
COMMON /BLKA/ PTIME,RTIME,PCON,RCON,PAM,RAM,IPT
COMMON /BLKC/ G0,SPD,NPULSES,IPA,RCS,REFAC,PFAC,THVAL
COMMON /BLKE/ AZBP,ELBP,TGTTEL,HEADING
COMMON /BLKH/ NOP,NOPTOTAL

```

 $L=0$

```
DO J=1, 2
  DO I=1, 20
    IWK(I,J)=0
  END DO
END DO
```

```
DO I=1, 20
      BIWK(I)=0.
END DO
```

```
XR_OLD=REF(1,1)
YR_OLD=REF(1,2)
DELTIME TOTAL=0.
```

```
DO I=1, NR
```

SITE=LRVIS(I,1)	IReflector site number
MPATH_FLAG=LRVIS(I,2)	I Multipath indicator
XR=REF(SITE,1)	IReflector x coord
YR=REF(SITE,2)	IReflector y coord
RANGE=SQRT((XR-X0)**2+(YR-Y0)**2)	
RR=RANGE*SCALE_FAC	I Range in metres
B3=BLRVIS(I)	IReflector-ship angle

```

IF (B3.LT.0.) B3=B3+360.
DIFF=ABS(B3-REF(SITE,3))
IF (DIFF.GT.10.) DIFF=360.-DIFF
                                IDeg off reflector bearing
                                I1st, 4th quadrants

IF (DIFF.LE.10.) THEN
    RCS1=RCS*(1.-.05*DIFF)
    CON1=REFAC*RCS1
                                IModify rcs due to aspect angle
                                IConstant with modified RCS
ELSE
    RCS1=0.
END IF

IF (I.EQ.1) THEN
    IF (NOPTOTAL.EQ.0) THEN
        IF (XR.EQ.XR_OLD .AND. YR.EQ.YR_OLD) THEN
            TI=0.
            DELTIME=0.
        ELSE
            CALL SUB1(RANGE,X0,Y0,XR,YR,XR_OLD,YR_OLD,SPD,TI)
            DELTIME=TI
        END IF
    ELSE
        IF (XR.NE.XR_OLD .OR. YR.NE.YR_OLD) THEN
            CALL SUB1(RANGE,X0,Y0,XR,YR,XR_OLD,YR_OLD,SPD,TI)
            DELTIME=DELTIME+TI
        END IF
    END IF
ELSE
    CALL SUB1(RANGE,X0,Y0,XR,YR,XR_OLD,YR_OLD,SPD,TI)
    DELTIME=TI
END IF

DELTIME_TOTAL=DELTIME_TOTAL+TI

PTIME=PTIME+DELTIME
RTIME=RTIME+DELTIME

TGTEL=ATAN2D(REF(SITE,6)-AHGT,RR)    ITarget elevation

CALL PRR(NPULSES)                    IPitch,roll subr

CALL BMPN(X0,Y0,XR,YR,RR,NPULSES,IPA) IBeam pattern subr

NHITS=0

DO J=1, NPULSES                      IAssume NPULSES hits/target

    TPR=0.                            ITotal power received

    IF (RCS1.NE.0. .AND. AZBP(J).NE.0. .AND. ELBP(J).NE.0.) THEN

        CON2=CON1*
        (G0*AZBP(J)*ELBP(J))**2I (modified antenna gain)**2
                                &
        DO M=1, 3                      IAssume max 3 reflectors/site

            RHGT=REF(SITE,M+5)          IHeight of reflector

            IF (RHGT.GT.0.) THEN
                SLRR=SQRT(RR**2+(RHGT-AHGT)**2) ISlant range
            
```

```

      PR=CON2/SLRR**4
      IF (MPATH_FLAG.EQ.1) PR=PR*16.* IPR modified by
      SIN(PFAC*RHGT/SLRR)**4      I propagation fac
      TPR=TPR+PR      ITotal power received
&      END IF

      END DO

      TPR=ALOG10(TPR)

      IF (RR.LE.480.) THEN
        N=1
      ELSE
        N=ININT((RR-480.)/360.)+1      IThreshold gate
        IF ((N-1)*360.+480..LT.RR) N=N+1
      END IF

      IF (TPR.GE.THVAL(N)) NHITS=NHITS+1

    END IF

  END DO

  IF (NHITS.GE.3) THEN      IDetection
    L=L+1
    IWK(L,1)=SITE
    IWK(L,2)=MPATH_FLAG
    BIWK(L)=BLRVIS(I)
  END IF

  XR_OLD=XR
  YR_OLD=YR

END DO

NR=L      I# of reflector sites detected

DO I=1, 20
  LRVIS(I,1)=IWK(I,1)      IReflector site number
  LRVIS(I,2)=IWK(I,2)      I Mpath_flag
  BLRVIS(I)=BIWK(I)      IReflector-ship angle
END DO

DELTIME=SPD*360.-DELTIME_TOTAL      ITime/scan-delttime_total

RETURN
END

SUBROUTINE SUB1(RANGE,X0,Y0,XR,YR,XR_OLD,YR_OLD,SPD,TI)

ACSQ=RANGE**2      I(XR-X0)**2+(YR-Y0)**2
BCSQ=(XR_OLD-X0)**2+(YR_OLD-Y0)**2
ABSQ=(XR-XR_OLD)**2+(YR-YR_OLD)**2
AC=RANGE      ISQRT(ACSQ)
BC=SQRT(BCSQ)
VAL=(ACSQ+BCSQ-ABSQ)/(2.*AC*BC)
IF (VAL.GE.1.0) THEN
  ANGLE=0.

```



```
ELSE IF (VALLE.-1.0) THEN  
  ANGLE=180.  
ELSE  
  ANGLE=ACOSD(VAL)  
END IF  
TI=SPD*ANGLE  
  
RETURN  
END
```

COMMUNICATIONS RESEARCH LABORATORY
McMASTER UNIVERSITY

NAME: SUBROUTINE PREC

PURPOSE:
Calculate precision and reliability of range measurements for given reflector geometry

CALL: CALL PREC(X0,Y0)

WHERE:
X0 - Ramtek coord of vessel (col coord of array MAP)
Y0 - Ramtek coord of vessel (row coord of array MAP)

```

SUBROUTINE PREC(X0,Y0)
IMPLICIT INTEGER*2 (I-N)
REAL REF(20,14),BLRVIS(20)
REAL A(20,2),W(20),R(20),WK(5)
INTEGER*2 LRVIS(20,2),SITE
COMMON /BLK4/ REF,NREF,THETA,SCALE_FAC
COMMON /BLK6/ LRVIS,BLRVIS,NR
COMMON /BLKF/ SIG,SIG1
COMMON /BLKH/ NOP,NOPTOTAL
COMMON /BLKI/ ERR,ERRTOTAL,EMAX,EMIN,NX1,NY1,NX2,NY2

```

```
DO J=1, 2
  DO I=1, 20
    A(I,J)=0.
  END DO
END DO
```

Initialize design matrix

```
DO I=1, 20
  W(I)=0.
  R(I)=0.
END DO
```

Initialize covariance vector
Initialize reliability vector

```
DO I=1, 5
    WK(I)=0.
END DO
```

Initialize work vector

```
IFLAG=0
NOPTOTAL=NOPTOTAL+1
NOP=NOP+1
```

```

DO I=1, NR                                IForm A, W matrices
SITE=LRVIS(I,1)                           IReflector site number
DELX=X0-REF(SITE,1)
DELY=Y0-REF(SITE,2)
RANGE=SQRT(DELX**2+DELY**2)               IShip-reflector range
A(I,1)=DELX/RANGE                         IDesign matrix
A(I,2)=DELY/RANGE
W(I)=1./((RANGE*SCALE_FAC*SIG1)**2+SIG)  ICovariance matrix
END DO

```

```

DELX=X0-990                                IMargaree site
DELY=Y0-695
RANGE=SQRT(DELX**2+DELY**2)
A(NR+1,1)=DELX/RANGE
A(NR+1,2)=DELY/RANGE
W(NR+1)=1./((RANGE*SCALE_FAC*SIG1)**2+SIG)
DELX=X0-44                                I site 6
DELY=Y0-421
RANGE=SQRT(DELX**2+DELY**2)
A(NR+2,1)=DELX/RANGE
A(NR+2,2)=DELY/RANGE
W(NR+2)=1./((RANGE*SCALE_FAC*SIG1)**2+SIG)

NRP2=NR+2

DO I=1, NRP2                                IForm AtWA matrix

    WK(1)=WK(1)+W(I)*A(I,1)**2              I(1,1)
    WK(2)=WK(2)+W(I)*A(I,1)*A(I,2)          I(1,2)=(2,1)
    WK(3)=WK(3)+W(I)*A(I,2)**2              I(2,2)

END DO

WK(4)=WK(1)*WK(3)-WK(2)**2                  IDet(AtWA)

WK(5)=WK(1)                                IForm AtWA inverse
WK(1)=WK(3)/WK(4)                          I(1,1)
WK(2)=-WK(2)/WK(4)                          I(1,2)=(2,1)
WK(3)=WK(5)/WK(4)                          I(2,2)

SIGMAX=SQRT(.5*(WK(1)+WK(3)+
& SQRT((WK(1)-WK(3))**2+4.*WK(2)**2)))      IPrecision

SIGMAX95=2.447*SIGMAX                      I95% confidence interval

ERR=ERR+SIGMAX95                            IError for track I
ERRTOTAL=ERRTOTAL+SIGMAX95                  ITotal error

IF (SIGMAX95.GT.EMAX) THEN
    EMAX=SIGMAX95                            IValue and
    NX1=ININT(X0)                            I location of
    NY1=ININT(Y0)                            I max error
END IF

IF (SIGMAX95.LT.EMIN) THEN
    EMIN=SIGMAX95                            IValue and
    NX2=ININT(X0)                            I location of
    NY2=ININT(Y0)                            I min error
END IF

DO I=1, NRP2                                IReliability factors
    R(I)=SQRT((WK(1)*A(I,1)**2+
& 2.*WK(2)*A(I,1)*A(I,2)+
& WK(3)*A(I,2)**2)*W(I))
    IF (R(I).GE..9) IFLAG=1
END DO

IF (SIGMAX95.GE.7.5 .OR. IFLAG.EQ.1) THEN
    WRITE(2,(' Test point ("I4,"",I4,

```

```

&      ")",8X,"Precision = ",F6.2,8X,"Sites :","2014)")
&      ININT(X0),ININT(Y0),SIGMAX95,(LRVIS(M,1),M=1,NRP2)
C      WRITE(2,(" Multipath      : ",20I5')) (LRVIS(M,2),M=1,NRP2)
C      WRITE(2,(" Reliability    : ",20F5.2')) (R(M),M=1,NRP2)
      END IF

      WRITE(3) ININT(X0),ININT(Y0),SIGMAX95

      RETURN
      END

```

REFERENCES

1. Greenlay, T. and Haykin, S., 'On the Design of Passive Retro-Reflectors for use with Precise Radar Navigation Systems', TDC Report TP4507, McMaster University, April, 1983.
2. Macikunas, A., Haykin, S. and Greenlay, T., 'Trihedral Twist Reflector', patent application, Oakville, Ontario, February 9, 1984.
3. Macikunas, A., 'Passive Polarimetric Reflector for Precise Radar Navigation', M.Eng. Thesis, March, 1985.
4. Cho, R., Haykin, S. and Greenlay, T., 'POLARIMETRIC RADAR FOR PRECISE NAVIGATION (PRAN): Study of an Experimental System', TDC Report TP7632E, McMaster University, April, 1986.
5. Hannan, P., Jasik, H. and Woodland, K., 'Twist Reflector', U.S. Patent Number 3,161,879, December 15, 1964.
6. Kreyszig, E., 'Advanced Engineering Mathematics', John Wiley & Sons, Inc., New York, 1972.

LIST OF ABBREVIATIONS

CHL	Christiaan Huygenslaboratorium
cm	centimetre
CRL	Communications Research Laboratory
D/A	digital/analog
dB	decibel
DMA	Dominion Marine Association
GHz	gigahertz
GPIO	general purpose input-output
IF	intermediate frequency
m	metre
MHz	megahertz
mm	millimetre
MPBT	MPB Technologies, Inc.
NAVFIX	Precise Radar Integrated Navigation System
ns	nanosecond
OSL	Offshore Systems Limited
PINS	Precise Integrated Navigation System
PPI	plan position indicator
PRAN	Polarimetric Radar for Accurate Navigation
PRF	pulse repetition frequency
RF	radio frequency
STC	sensitivity time control
TDC	Transportation Development Centre of Transport Canada
TR	transmit-receive

APPENDIX B

Trihedral Radar Reflector (TRR)
Final Report MPBT-287-01



TRIHHEDRAL RADAR
REFLECTOR (TRR)

Final Report
MPBT-287-01

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Report No. 287-01
March 1989

Approved by:

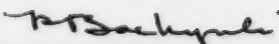

Dr. M.P. Bachynski
President

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1.0 INTRODUCTION

This report concludes an R&D programme by MPB Technologies Inc. to design, construct and test a Trihedral Radar Reflector (TRR) which incorporates a "Twist-Grid" to cross-polarize the return signal thereby enhancing the target discrimination in high clutter areas.

The reflector was designed to comply with the requirements of Offshore Systems Ltd. as described in their Request for Quotation (OSL, 20 August, 1987).

The principal objective of the program was to produce a cost-effective design, applicable to a small production quantity of twenty units for field trials.

2.0 DETAILED DESIGN DESCRIPTION AND PARTS LIST

An engineering assembly drawing, TRR-100 (Fig. 1) shows the construction and assembly details along with a Parts List (Fig. 2).

Sheet metal fabrication was chosen primarily for the the low setup costs required for small quantity production. The dimensional tolerances achieved with this technique are well within the required specification of $90^{\circ} \pm 0.25^{\circ}$.

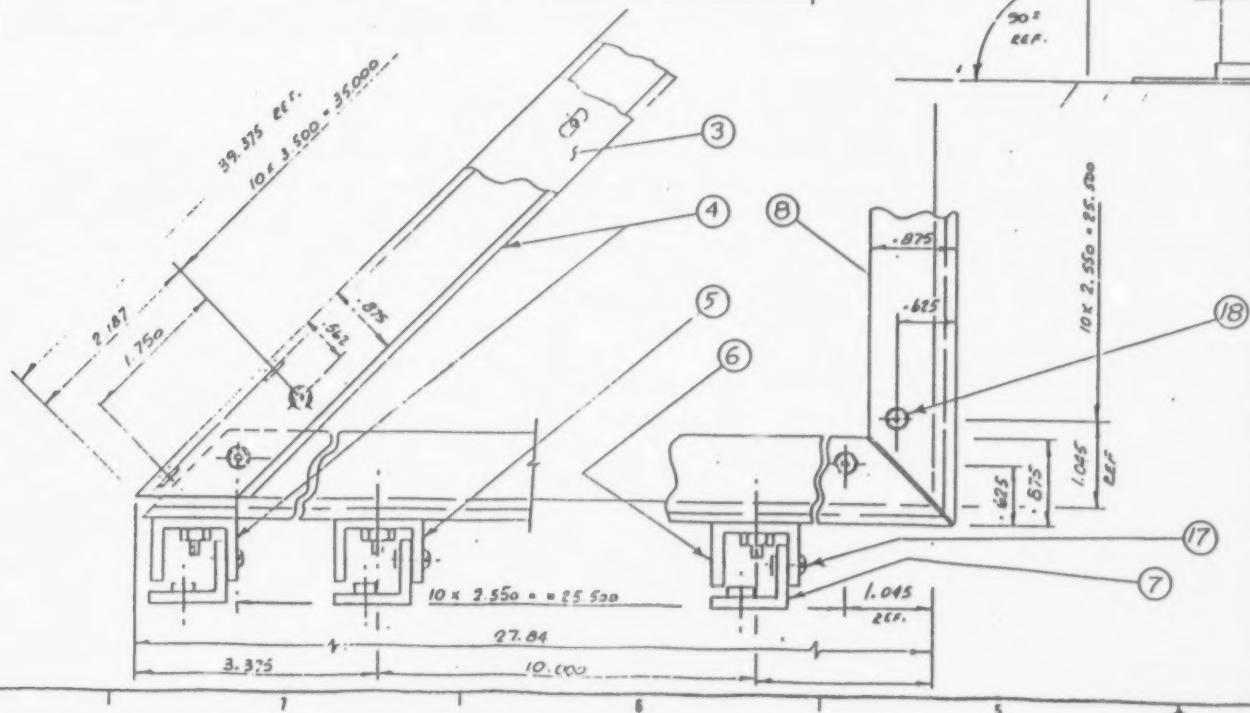
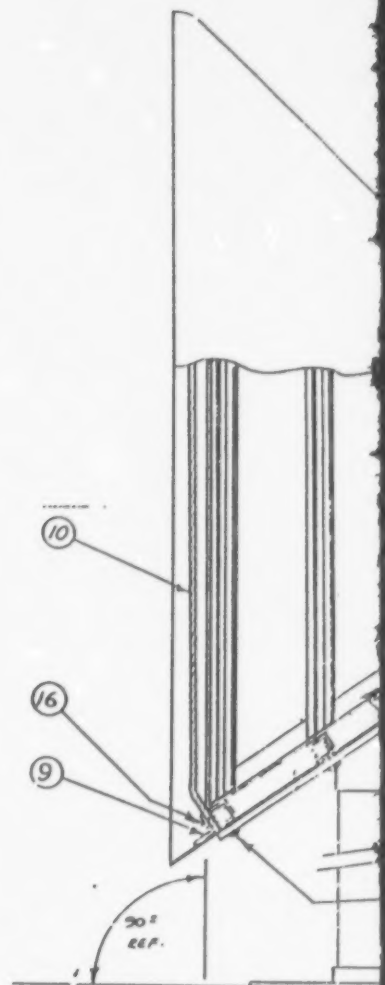
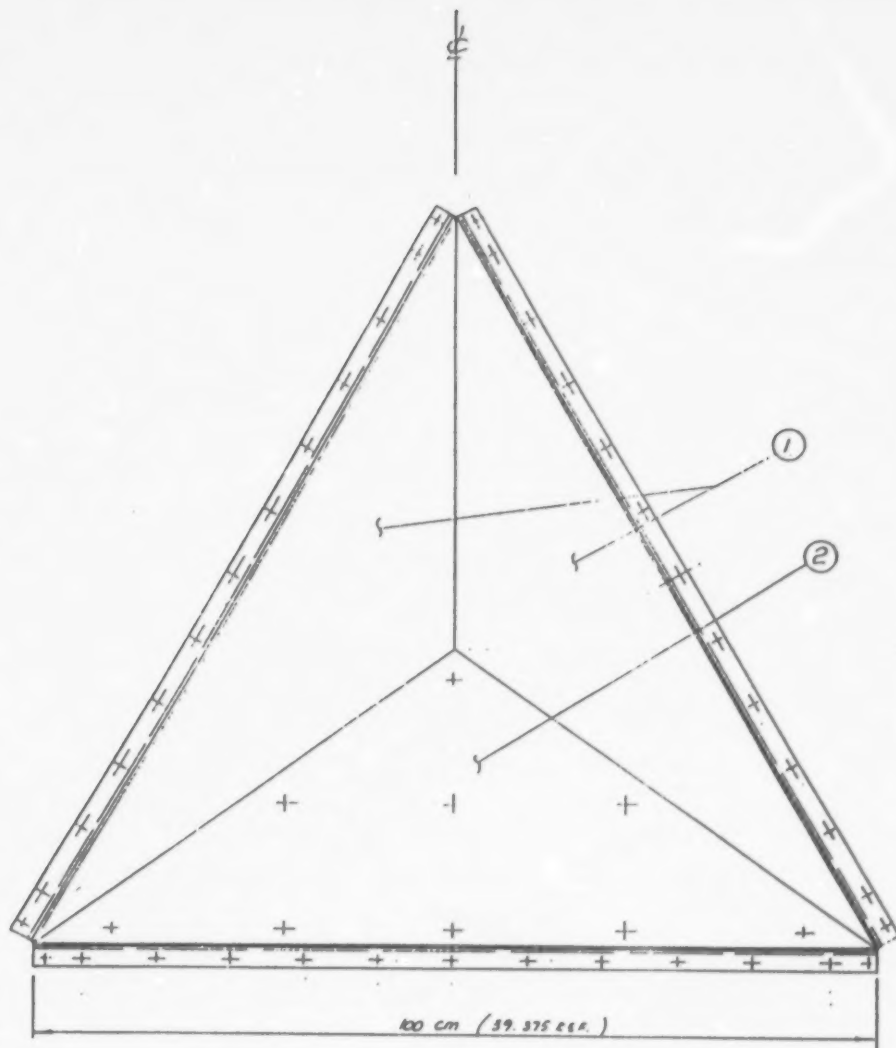
A clear anodized finish was used to protect the reflecting surfaces from corrosion. This finish was chosen because previous tests with other microwave systems has shown that the anodizing has no measurable effect, even at higher frequencies. The surface roughness (~ 32 micro inch RMS) is approximately one thousand times better than the normally accepted specifications of $\lambda/40$ for microwave reflectors.

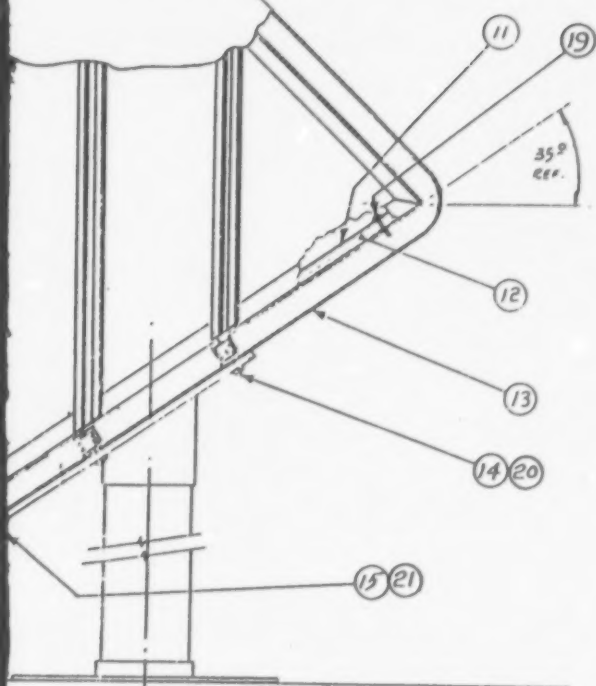
The "twist-grid" consists of a conductive silver epoxy, layed down in narrow traces on a thin polyester (Mylar) film using a standard silk screen process. A layer of "peel-and-stick" silicone adhesive is applied over the traces and the film is then bonded, face down, to a 1.7 mm thick sheet of styrofoam-SM. This "sandwich" assembly is then cut to the exact size of one of the reflecting surface plates with the traces running parallel to one of the short edges of the plate. Nylon screws are used to secure the grid assembly in place. The intersecting edges of the reflector plates, as well as all the exposed edges of the twist-grid assembly, are sealed with a clear silicone caulking compound.

The radome is made from 1/2" thick closed-cell, polyethylene foam sheet (2.0 lbs. density) with the original factory skin surface on both sides. This material has microwave properties very comparable to low-density styrofoam, with no perceptible loss at 10 GHz and remains flexible at temperatures below -40°C . The radome is installed with an exterior angle frame to compress the foam against the front edge of the reflector and form a watertight seal.

A fiberglass weather-hood encloses the reflector, extending beyond the front surface, to provide some degree of protection for the radome against rain and sleet.

Six 1/4-20 bolts are provided as attachment points, on each of the three back surfaces of the TRR, to support and position the reflector depending on the installation configuration.





PART N°	ITEM	QTY
1	DWG. MPB TER 101-01	2
2	" -02	1
3	" 102-01/06	9
4	" -01	3
5	" -02	3
6	" -03	3
7	" -08	18
8	" -07	3
9	" -09	3
10	POLYETHYLENE FOAM RADIOTE	1
11	SILK-SCREEN GRID	1
12	STYRAFOAM 3/4" SPACER	1
13	FIBREGLASS WEATHER HOOD	1
14	BOLT, 1/4-20X1" HEX. S.S.	18
15	SCREW, 6-32X1/2" TRUSS, S.S.	33
16	" " 1" " "	39
17	" 8-32X1/2" " "	36
18	NUT, 6-32 NYLON S.S.	135
19	SCREW, 6-32X1" NYLON	9
20	WEATHER-SEAL WASH, 1/4" S.S.	18
21	" " #6, "	33

FIG. 1

DRWN / DESS / SWS. 3100-27
 CH'D / VER B.G. 885
 DATE 10 NOV 87 S/0-257

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MPB

MPB TECHNOLOGIES INC.
 DORVAL
 QUÉBEC, CANADA

TITLE / TITRE

TETRAHEDRAL RADAR REFLECTOR
 (TER) ASSY.

D TER-100

FIGURE 2: Parts List (Ref. Dwg. #TRR-100)

PART NO.	ITEM	SOURCE	QTY.
01	Reflector Side Plates	Shop Fabrication	2
02	Reflector Bottom Plates	Shop Fabrication	1
03	Reflector Spacer Strips	Shop Fabrication	9
04	Reflector Front Channel	Shop Fabrication	3
05	Reflector Mid Channel	Shop Fabrication	3
06	Reflector Rear Channel	Shop Fabrication	3
07	Reflector Support Brackets	Shop Fabrication	18
08	Reflector Corner Angles	Shop Fabrication	3
09	Reflector Radom Frame	Shop Fabrication	3
10	Polyethylene-Foam Radome	"Ethafom-#220", DOW.	1
11	Silk-Screen Grid, Film	Supplied by OSI	1
12	Styrofoam "SM" Spacer	Induspac, Lachine, Que.	1
13	Fibreglass Weather Hood	USIFIBRE, P.G.C., Inc.	1
14	Bolt, 1/4-20 x 1", Hex. HD.S.S.	SPAE-NAUR	18
15	Screw, 6-32x1/2", Truss HD.S.S.	SPAE-NAUR	33
16	Screw, 6-32x1", Truss HD.S.S.	SPAE-NAUR	39
17	Screw, 8-32x1/2", Truss HD., S.S.	SPAE-NAUR	36
18	Nut, 6-32, "Nylok", S.S.	SPAE-NAUR	135
19	Screw, 6-32 x 1", Nylon	SPAE-NAUR	9
20	"Weather-Seal" Wash., 1/4" S.S.	SPAE-NAUR	18
21	"Weather-Seal" Wash., #6, S.S.	SPAE-NAUR	33

3.0 TEST PROCEDURES

3.1 Lab Tests

3.1.1 Grid Transmission

A test facility was set up (Fig. 3) to evaluate the transmission performance of three different test grids for incident polarization parallel and perpendicular to the grid orientations. In the case of the parallel orientation, the transmission loss rather than the actual reflected signal was measured. The plane of the grid was set at a 35° angle to the direction of propagation to duplicate the final configuration.

Since the "ideal" twist-grid should totally reflect waves with electric vector parallel to the grid and totally transmit those whose electric vectors are perpendicular, this first test was conducted to measure the performance of grids with different spacing and trace widths and compare to the theoretically predicted performance.

The results (Table I) show that the transmission through the grids for the perpendicular component is essentially unattenuated (less than 0.1 dB loss). However, the reflectivity of the parallel component significantly improves as the spacing(s) decreases (11 dB to -20 dB trans. loss). The width (W) of the traces appears to have little effect which is consistent with existing theory.

TABLE 1: Transmission loss for test grids

MPB GRID No.	WIDTH (W)	SPACING (S)	PARALLEL TRANS. LOSS	PERPEND- ICULAR TRANS. LOSS
#1	0.5 m.m.	5.5 m.m.	less than 0.1 dB	~11 dB
#2	1.0 m.m.	4.0 m.m.	less than 0.1 dB	~15 dB
#3	0.5 m.m.	3.0 m.m.	less than 0.1 dB	~20 dB

The preliminary indication from these results was that the #3 (close spaced) grid was the most suitable since it was 99% efficient for both parallel and perpendicular polarization components.

3.1.2 Polarization Conversion

A second facility (Fig. 3) was used to measure the conversion efficiency and determine the optimum distance (L) of the grid above the reflecting surface.

The distance between each horn and the reflecting surface was chosen to ensure that the measurements were in the far field. Sheets of microwave absorber were used to eliminate unwanted reflections and to verify that the twist-grid was large enough to cover the full main beam footprint and that no indirect or multi-path signal was producing a false result.

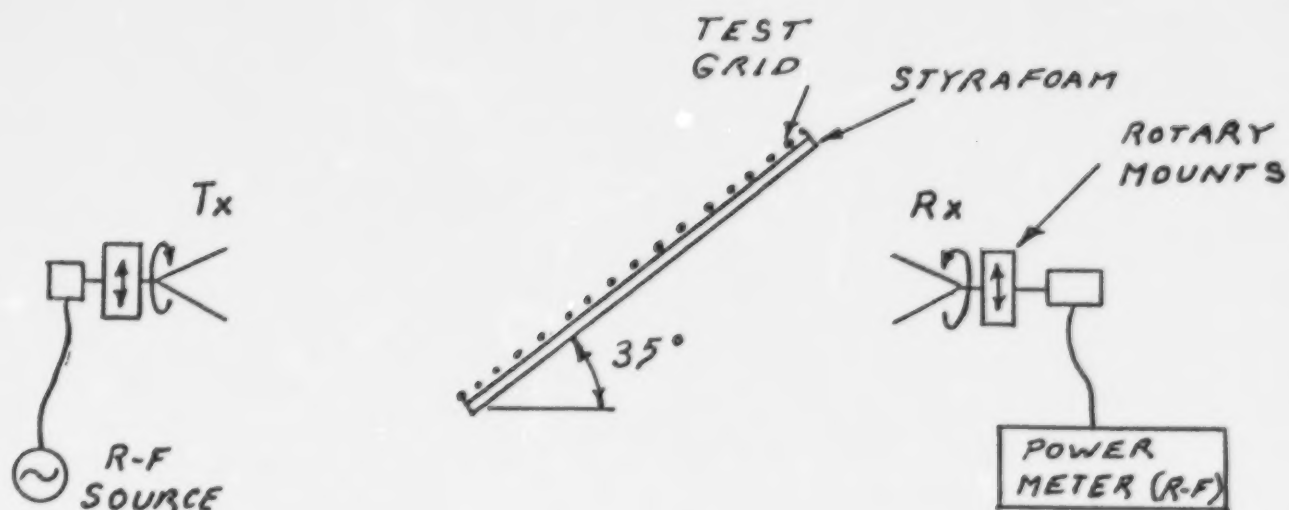


FIGURE 3(a): Twist-Grid transmission test facility

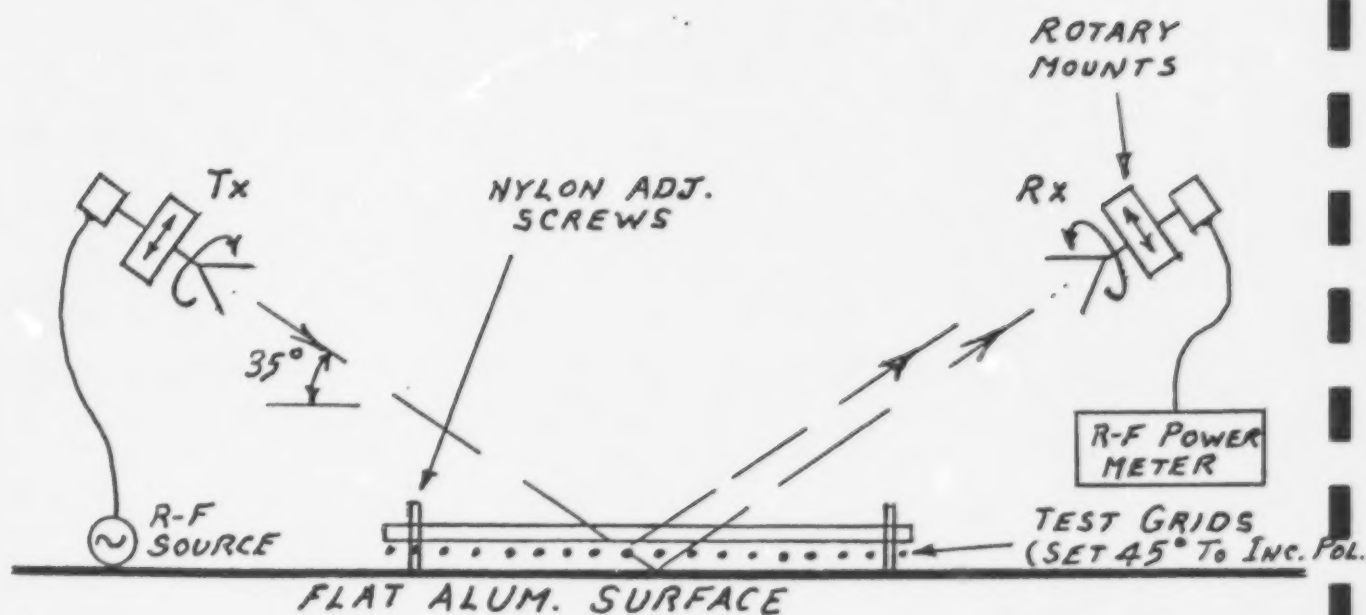


FIGURE 3(b): Test facility for evaluation of twist-grid polarization conversion efficiency.

Because this type of measurement is very sensitive to the flatness and angle of the reflecting surface, exact quantitative results are difficult to achieve without a more extensive test facility. However, the results summarized below, were sufficiently consistent and reproducible to make an adequate comparison of the various grids.

Conversion Efficiency:

All three grids were comparable in polarization conversion within -0.5dB to -0.2 dB of total conversion. By optimizing the distance (L) above the reflecting surface and slightly adjusting the 45° incident polarization angle, a conversion efficiency in the range of 90% to 95% could be achieved.

Distance (L) Above Surface:

The optimum distance (L) was found to be more critical in tolerance as the grid spacing(s) became closer. Grid #1 (wide space) = 17mm $\pm$ 4mm and grid #3 (close space) = 15mm $\pm$ 1mm.

This is not unexpected, since the electrical interface formed by the wire grid would become less spacially defined as the wires are separated.

Frequency Bandwidth:

Grid #1 was significantly more broadband than Grid #3 ($\pm$ 2 GHz compared to $\pm$ 0.5 GHz respectively).

Like Polarization (LPRR):

The level of the "like" polarization return was found to be extremely sensitive to the orientation and tilt of the grid plane above the reflecting surface. For all three grids the "like" polarization could be varied from about -8 dB to much less than -20 dB with a slight tilt and rotation of the grid. However, in every case a better LPRR resulted in a slight loss in conversion efficiency. The LPRR was also found to be sensitive to frequency.

Again this is not unexpected since the converted signal is the resultant of two orthogonal components, one reflected from the grid surface and the other from the back plane. Any difference in amplitude or phase of these two components reduces the conversion efficiency and increases the "like" polarized signal. For example a relatively small difference in amplitude of the two components could be corrected by tilting the corresponding reflecting surface and deflecting the return signal

away from the receiver. This would result in a slight reduction in the converted signal but a dramatic reduction in the "like" signal and, therefore, a significant improvement in the LPRR. Likewise, a slight rotation of the grid from the 45° orientation could balance the distribution of the incident radiation between the parallel and perpendicular components thereby nulling the "like" return signal. However, the resulting rotation in the plane of polarization would not be exactly 90°.

From the results of this second lab test, it was concluded that the #1 grid (5.5 mm spacing) was the most suitable since it was comparable in conversion efficiency but with a broader frequency bandwidth. As well, the grid to reflecting surface distance (L) was less critical and as a result would presumably have a larger beamwidth.

3.2 Preliminary Field Trials

The prototype reflector was mounted at the rear of the MPB Technologies Inc. location at Dorval, Quebec about 40 metres from the transmitter/receiver. There was no provision for measuring azimuth and elevation patterns but the reflector, as well as the transmitting and receiving horns could be manually rotated about the axis of symmetry to measure the "cross" and "like" polarization return.

Although the measurements were made under adverse winter weather conditions, the results appeared to confirm the lab tests. The "cross" polarization return was within 0.5 dB of the full return signal when the grid was oriented at 90° to incident polarization (i.e. equivalent to no grid) and the "like" polarization was less than -10 dB.

It was also noted that the maximum "cross" polarized signal occurred in a plane approximately 10° beyond the vertical. Correspondingly, the minimum "like" polarization signal level was 10° off horizontal in the same direction. This occurred when the plane of polarization of the transmitted signal was horizontal and the grid was set at 45°.

3.3 Final Measurements

The final measurements were conducted at MPB Technologies Inc., Antenna Test Facility in Ottawa. The outdoor facility is shown in Fig. 4.

60 m.

TRR-100
ON ROTARY
PLYWOOD
FRAME

AZ/EL/AZ
POSITIONER

PENTHOUSE

COMPUTER
CONTROL
&
MEASURE.

A.P.C.
MONITOR
HORN

OSC.
MIX.
Tx
Rx
ABSORBER
SHEET

M-50 BLDG.

FIGURE 4: Ottawa test facility used for final field measurements
of Trihedral Radar Reflector (TRR-100)

The TRR was mounted on an elevation over azimuth, antenna positioner at a distance of approximately 60 metres from the transmitting and receiving horns. The computer controlled measurement and recording system incorporates a Scientific Atlanta Model 1770 Programmable Microwave Receiver.

The TRR was mounted in the same plywood support frame, used in the preliminary field tests, and could be manually rotated about the axis of symmetry to set the grid projection angle.

Following the first set of tests (January 14/15, 1988), measurements were made to determine the RCS of the TRR-100 reflector in the linear cross-polarization mode (Figure 5). The available calibration sphere was too small (5 1/4 in.dia.) to make a direct replacement measurement at the far field distance of the TRR. Instead the sphere was measured at a distance of 23 feet and the reflector at a distance of 360 feet. Using the distance ratio 23/360, the RCS of the reflector was calculated.

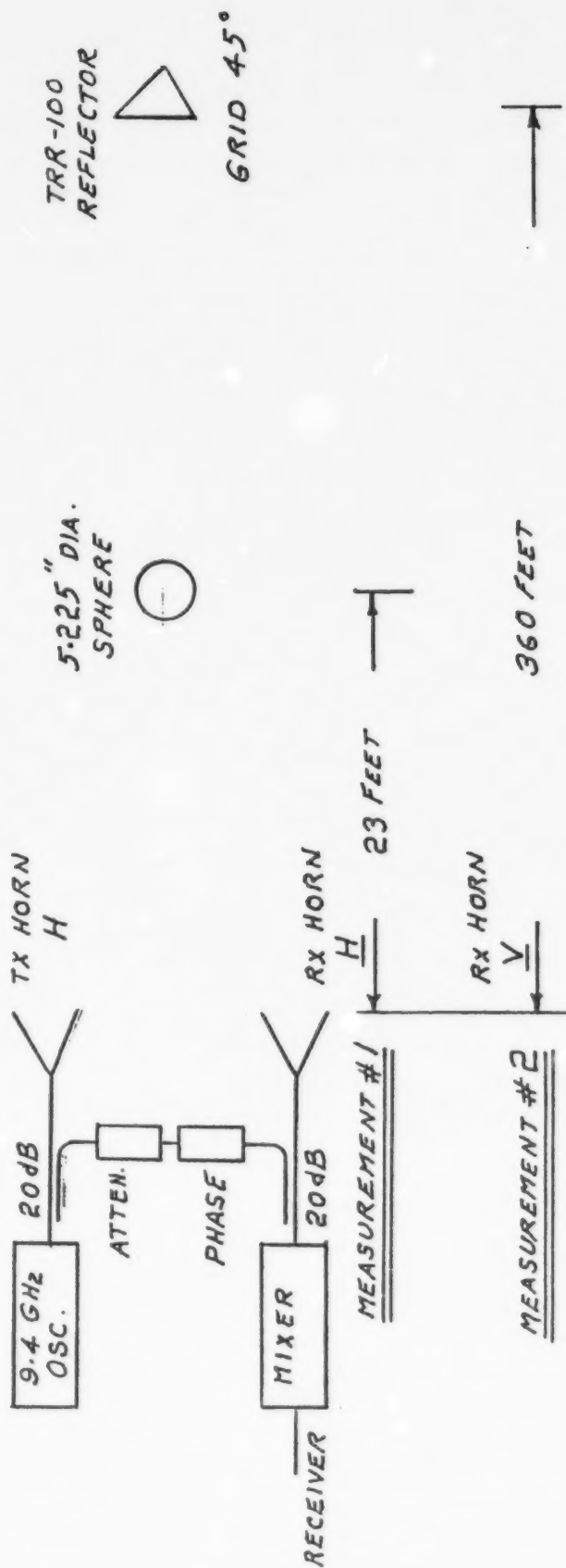


FIGURE 5: Field measurement configuration for RCS calibration of the Trihedral Radar Reflector.

The calibration sphere, with an RCS (A_1) of -18.6 dB SM at 9.4 GHz, gave a reflected power (P_1) of -17 dB (relative scale) from a range (R_1) of 23 feet. The corresponding return (P_2) from the reflector at a range (R_2) of 360 feet was -16 dB.

The reflector RCS (A_2) is therefore given by:

$$A_2 = \left(\frac{P_2}{P_1} \right) \left(\frac{R_2}{R_1} \right)^4 A_1$$

or:

$$10 \log_{10} P_2 - 10 \log_{10} P_1 + 10 \log_{10} \left(\frac{R_2}{R_1} \right)^4 + 10 \log_{10} A = 30.2 \text{ dB SM}$$

or: 1043 m^2

The experimental error for this measurement was expected to be ± 1 dB.

In response to a request by Offshore Systems Limited, an additional set of far field measurements were conducted to demonstrate the effectiveness of the TRR-100 for circular as well as linear polarization. The 9.6 GHz radar system was used with the TRR-100 reflector placed on the ground at a distance of 800 metres (Figure 6). The results in Table 5, show that the TRR-100 is effective for circular as well as linear mode of operation, as predicted. For circular polarization, the grid 2 can be set at any angle as compared to 45° for linear mode.

TABLE 5:			
TRANSMIT POL.	RECEIVE POL.	RECV. SIG. VOLTAGE	GRID ORIENTATION
HORIZ. LIN.	HORIZ.	160 mV	VERT.
HORIZ. LIN.	VERT.	20 mV	VERT.
LHC	LHC	150 mV	VERT.
LHC	RHC	80 mV	VERT.
RHC	RHC	150 mV	VERT.
RHC	LHC	100 mV	VERT.
HORIZ. LIN.	HORIZ.	60 mV	45°
HORIZ. LIN.	VERT.	190 mV	45°
LHC	LHC	160 mV	45°
LHC	RHC	80 mV	45°
RHC	RHC	160 mV	45°
RHC	LHC	100 mV	45°

$$dB = 10 \log \left(\frac{MV_1}{MV_2} \right)^2$$

I) January 14/15, 1988 Tests

This set of azimuth and elevation patterns was taken with the MPBT #1 grid installed in the engineering Model TRR (SCAN #106 to #130). The elevation patterns (SCAN #108, #109) were made by rotating the reflector and horns by 90°, denoted by GRID: 45° + 90°, 45° - 90°.

Scans #105, #112 and #118 were taken with the grid projection set perpendicular to the incident polarization. This gives an RCS equivalent to the reflector without the grid since the transmission loss through the grid at right angles is essentially zero. This measurement was repeated periodically to monitor the normalized signal level.

A comparison of Scan #105 and #107 shows a conversion efficiency of about 50 to 55% (2.5/3.0 dB down).

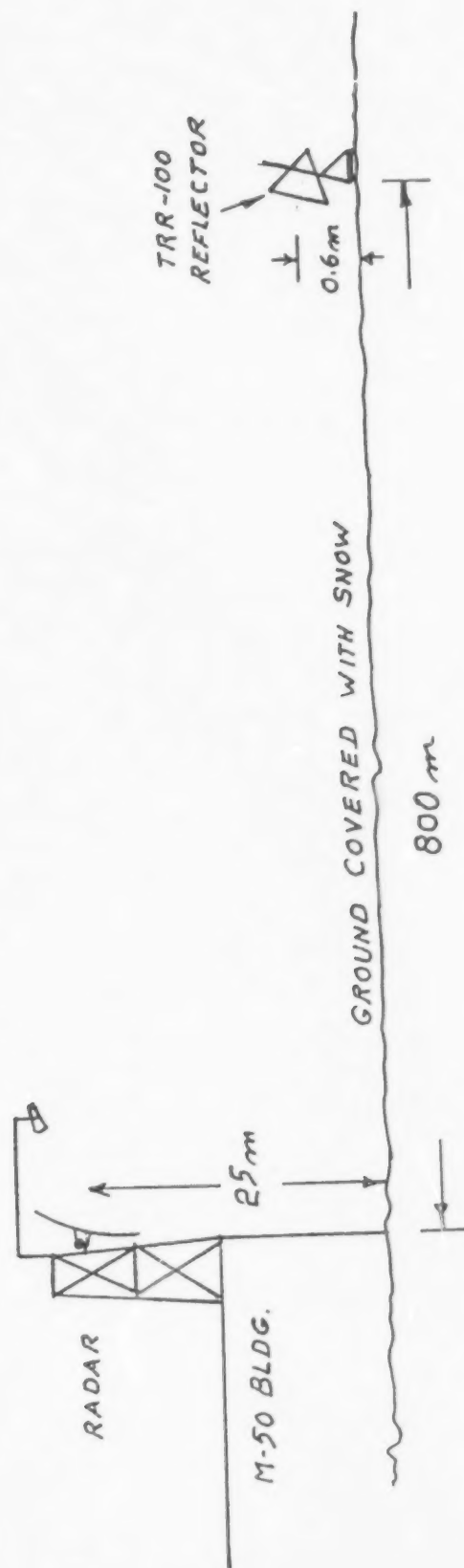


FIGURE 6: Radar range configuration for measuring circular polarization reflection performance of Trihedral Radar Reflector.

II) February 22, 1988 Tests

A further attempt was made to measure and compare the three grids (MPBT #1,2,3) mounted in the prototypes TRR. However, severe wind and cold temperatures made accurate, quantitative measurements difficult. The microwave absorber sheet, used to minimize cross-coupling between the transmitting and receiving horns, was vibrating in the gusting wind producing an unacceptably large noise background. A phase-nulling network was installed in place of the absorber but this proved unsuccessful and the measurements were postponed.

III) February 23, 1988 Tests

Due to the continuing bad weather conditions, an attempt was made to conduct some tests in the small (9m) indoor anechoic chamber. This chamber is equipped with a computerized system for range-gating and multi-path cancellation. However, the relatively short distance (~8m) between the transmitter/receiver and target produced severe phase interference effects and the results were inconclusive (see February 23, 1988 results).

IV) March 27, 1988 Tests

These measurements were essentially a repeat of the January 14, 1988 tests. Except in this case the TRR was one of the final production models complete with the radome, fiberglass hood and the twist-grid supplied by OSL. The normal elevation patterns were replaced with additional azimuth cuts at angles of $\pm 5^\circ$, $\pm 10^\circ$ and $\pm 15^\circ$. This not only avoided the need to rotate the reflector and horns due to the limited travel on the positioner movement but gave a truer representation of the actual end-use requirement.

Scans #173 and #177 show the return signal levels when the incident polarization is perpendicular to the grid and parallel to the grid, respectively. This gives a comparative measure of the perpendicular and parallel components of the retro-reflected radiation. It should be noted that the parallel component is significantly smaller than the perpendicular component by 5 to 6 dB.

This may be partly explained intuitively by the fact that only a portion of the incident parallel component of radiation is intercepted by the twist-grid. The reflecting grid surface forms a smaller trihedral reflector with a reduction in RCS of about 10%.

The RCS is proportional to $(r)^4$ where r = edge length.

Trihedral with no grid, $r = .707$ m (MPBT TRR-100)

Trihedral formed by grid, $r = .707$ m $- .017$ m = $.690$

$$\text{Ratio of RCS} = \frac{(.690)^4}{(.707)^4} = 0.907 = 90.7\%$$

As well the 10% portion that is not intercepted by the grid would be reflected by the second surface, 180° out of phase, likely causing a further reduction in the retro reflected parallel component.

V) July 4, 1988 Tests

These measurements were the result of tests being conducted on a separate project while using the TRR as a test target.

The significance of this test was that it was conducted over a longer range distance (120m) with a more directive source antenna (modified large dish). The result was a larger signal to clutter ratio and a more accurate measure of the "like" polarization.

The small "spike" at the centre of the pattern is the result of phase interference, occurring at normal incidence, caused by the reflection from the flat surfaces (TRR frame, support structure, etc...). This spike disappears when the reflector is tilted slightly and increases in amplitude at the shorter range distance (see March 27, 1988 tests).

4.0 RECOMMENDATIONS

Although we were required by the limitations of the contract, to comply with a restricted design approach, we feel that other alternative techniques should be considered. If future requirements involve larger production quantities or require improved target discrimination, the following comments may be of interest.

1) Construction Techniques

For larger quantities, a rigid plastic-foam moulding process could be used. This technique would require more expensive setup costs but could significantly reduce individual unit cost. This method would also guarantee dimensional accuracy and reproducibility.

2) Corrugated Reflector

The wire grid and foam spacer could be replaced by a corrugated or finned surface design which may have certain construction advantages for some fabrication processes.

3) Circular Polarization

As described in the original patent application by "Hannan" et al (Jan. 5, 1961, Ser. No. 80,961) the "twist-grid" can be used to convert the incident polarization for circular as well as linear polarized signals. It can also be used to convert linear polarization to circular polarization or circular to linear depending on the orientation and position of the grid.

In the case of the TRR-100, the present grid configuration will work equally well for either linear or circular polarization.

4) Alternative Approach

For navigational radar targets the principle requirement is target discrimination over a wide beamwidth in the azimuth direction and a moderate beamwidth in elevation. Although a totally passive reflector is desirable it may not necessarily be essential or cost-effective in an over-all system design.

A design incorporating an oscillating dihedral reflector would produce a pulsating signal, with a beamwidth of approximately 90° in the azimuth and 10° to 20° in elevation depending on the tilting motion.

Although this system would require a small power source, it would fulfill the requirement of beamwidth and discrimination and could be used with either linear or circular polarization without the need of a twist-grid.

The dihedral reflector itself could be of lightweight construction with a stationary radome type enclosure for weather protection.

The RCS would be 20 times larger than the "converted" RCS of the TRR-100 for approximately the same physical size.

$$\text{Practical RCS of TRR-100} = \frac{4\pi a^4}{3^2} \times \text{CONV.EFF} = \frac{4(.707)}{3(.0315)^2} \times 60\% = 633m^2$$

$$\text{Practical RCS of Dihedral} = \frac{8a^2b^2}{2} \times \text{RETROEFF} = \frac{8(.707)^2}{(.0315)^2} (1.0)^2 \times 100\% = 12660m^2$$

This "lighthouse" technique would produce a relatively large reflected signal with a predetermined pulse rate for comparatively simple target discrimination.

5.0 CONCLUSION

The objective of this programme was to produce a relatively low cost Trihedral Radar Reflector and deliver twenty field units within a limited schedule and cost budget.

In view of these restrictions, MPB Technologies Inc. proposed a design for a slightly larger reflector with approximately 50% more RCS than the one specified in the RFQ. Our intention was to provide the same or higher absolute cross-polarized signal return requested but with, what we considered, a more realistic conversion efficiency.

With the acceptance of this proposed approach by OSL, we feel that the test results confirm that the model TRR-100 reflector meets the principle, electrical performance objectives.

The measured dimensional accuracy of the prototype TRR-100 is less than $\pm 1.0\text{mm}$ deviation from the "ideal" trihedral in both flatness and orthogonality. Well within the required specification of $90^\circ \pm 0.25^\circ$, which translates to $\pm 3.0\text{ mm}$ at the extreme front edges of the trihedral. In fact this prototype unit performed very well as a retro target in 94 GHz radar tests, indicating that the dimensional accuracy and reflecting properties are more than adequate for 10 GHz operation.

6.0 TEST RESULTS OF FINAL MEASUREMENTS

I - January 14/15, 1988

II - February 22, 1988

III - February 23, 1988

IV - March 27, 1988

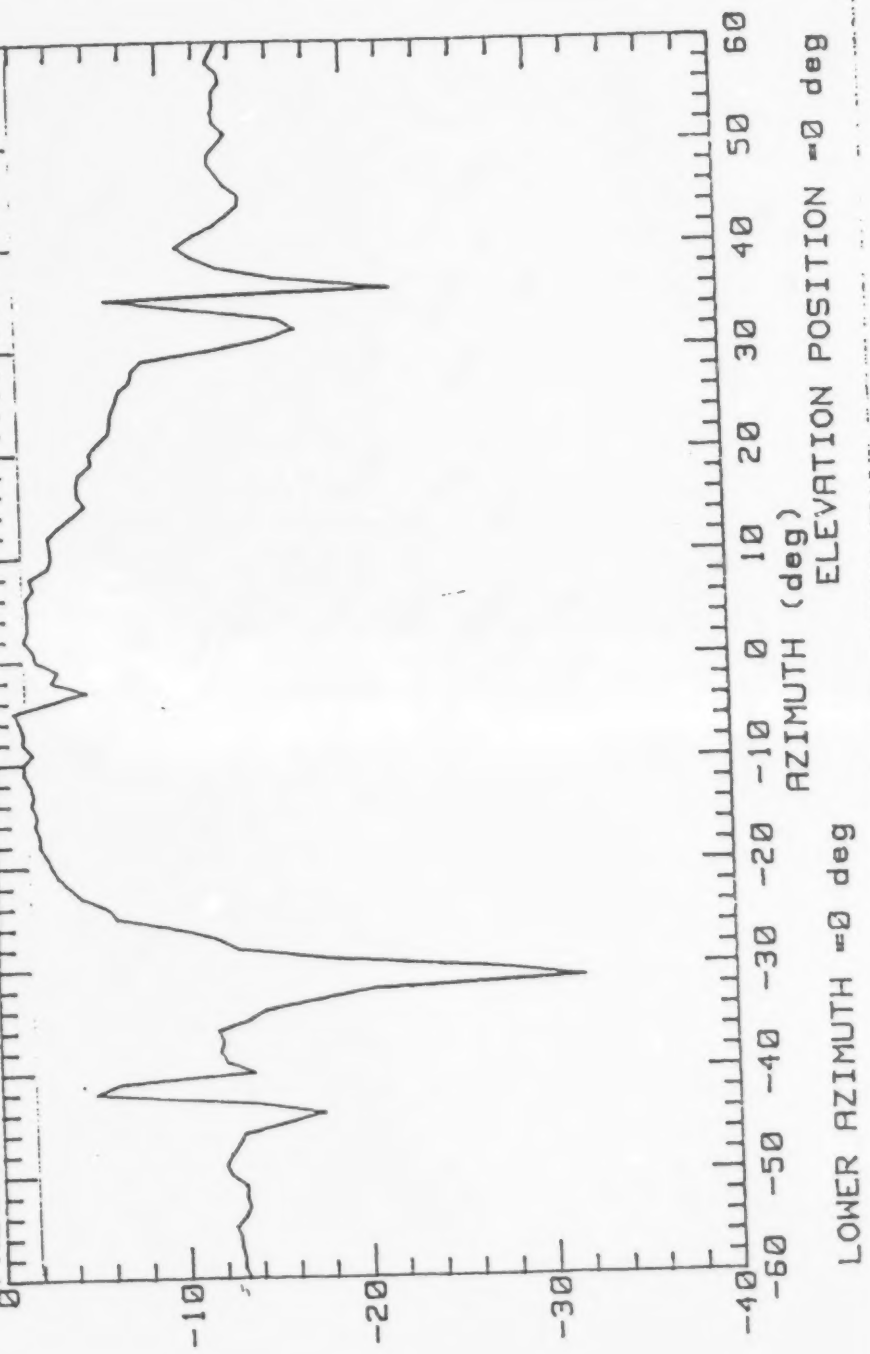
V - July 4, 1988

1

MPB
TECHNOLOGIES INC.

MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #1
Tx.H Rx.H GRID 90.Deg. (V) ABSORBER BETWEEN HORNS

FREQUENCY = 9.4 GHz



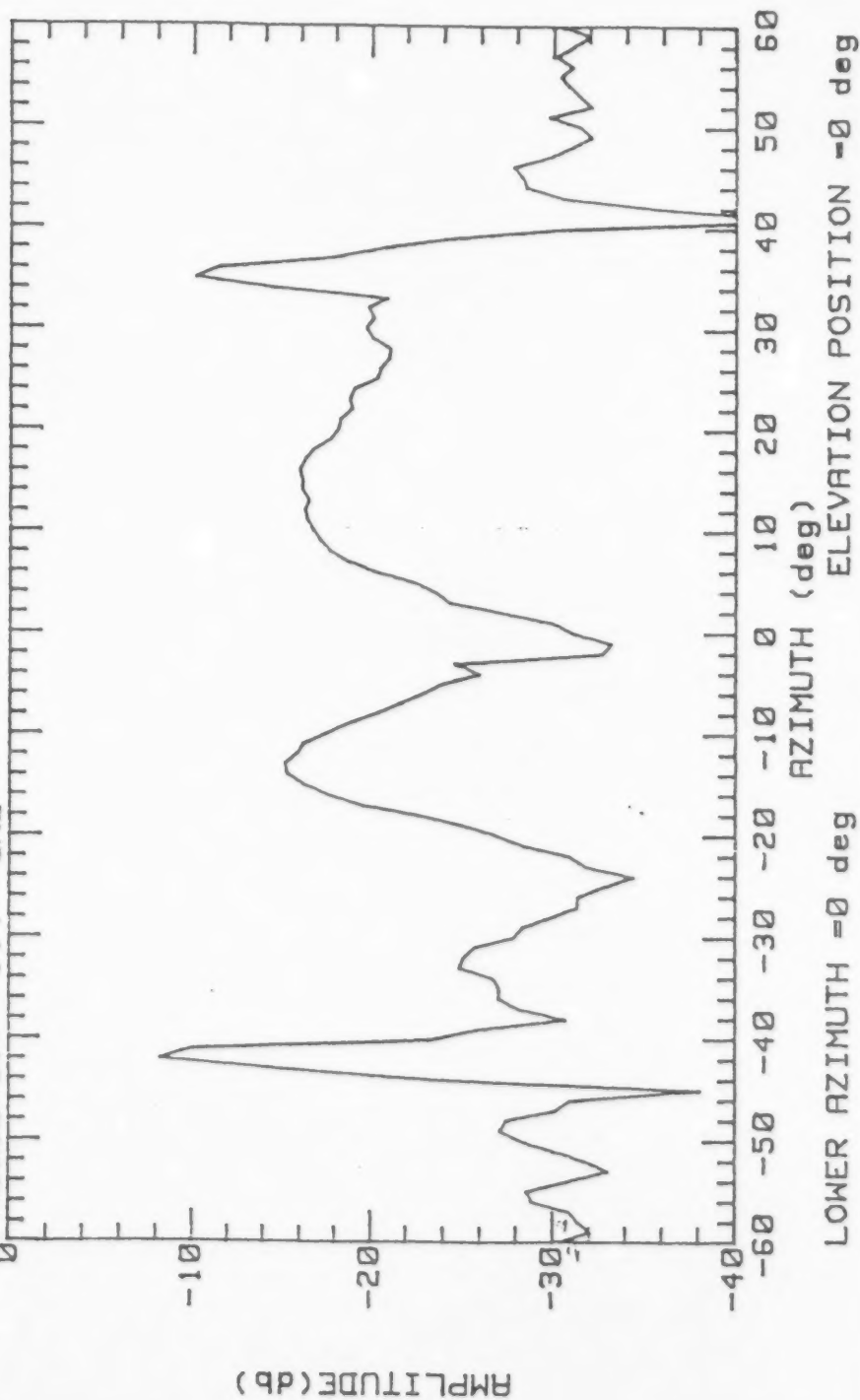
MPB TECHNOLOGIES INC. Exp. 1055CAN 1 BY: L. ALLAN

ON 14 Jan 1988 15:14:50



MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #1
TECHNOLOGIES INC. Tx.H Rx.V GRID 90.Deg.(V) ABSORBER BETWEEN HORNS

FREQUENCY= 9.4 GHz



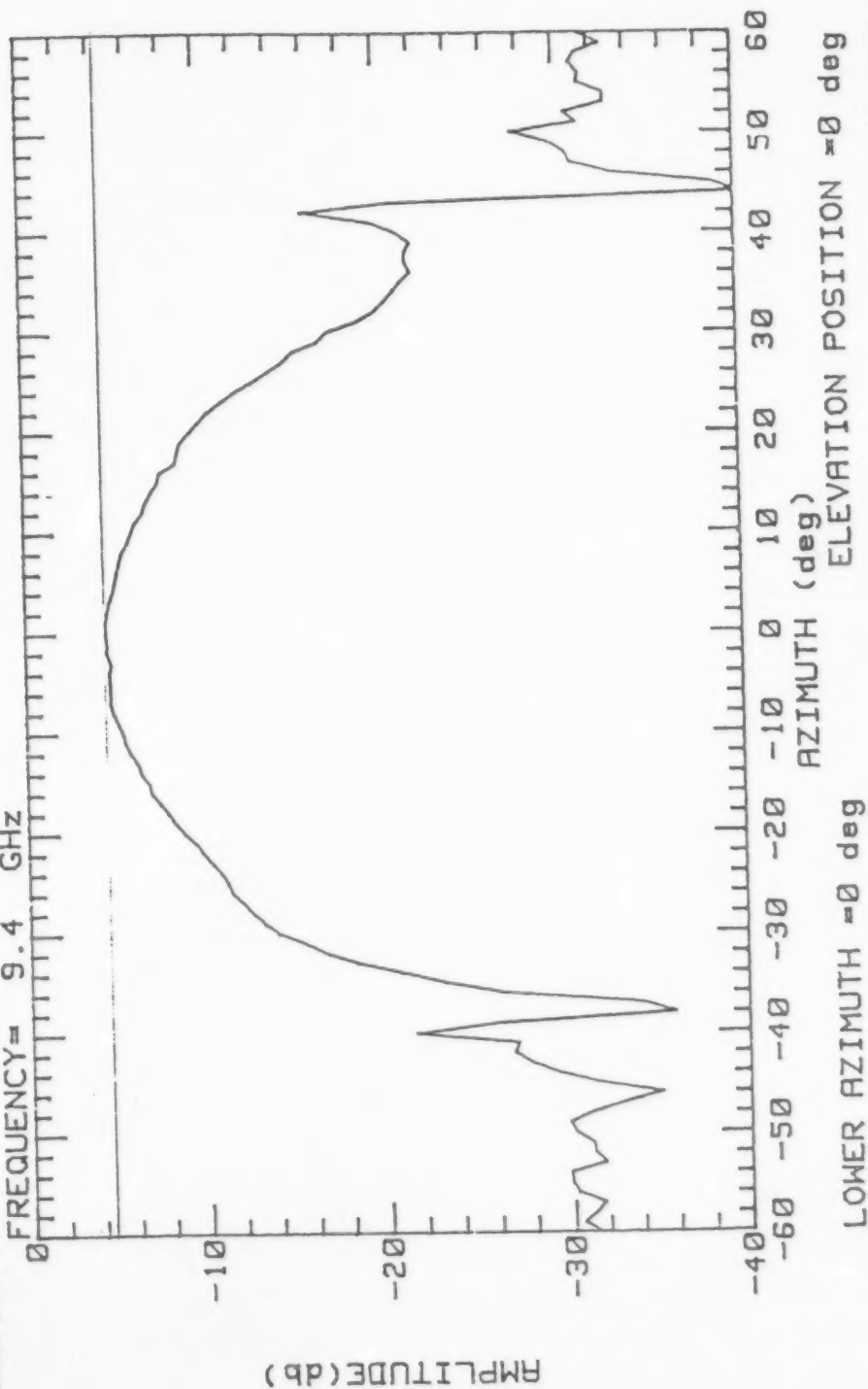
MPB TECHNOLOGIES INC. Exp.106SCAN 1 BY:L. ALLAN

ON 14 Jan 1988 15:20:37



TECHNOLOGIES INC.

MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #1
Tx..H Rx..V GRID 45.Deg.() ABSORBER BETWEEN HORNS
FREQUENCY= 9.4 GHz



MPB TECHNOLOGIES INC. Exp.107SCAN 1 BY:L. ALLAN

ON 14 Jan 1988 15:26:13

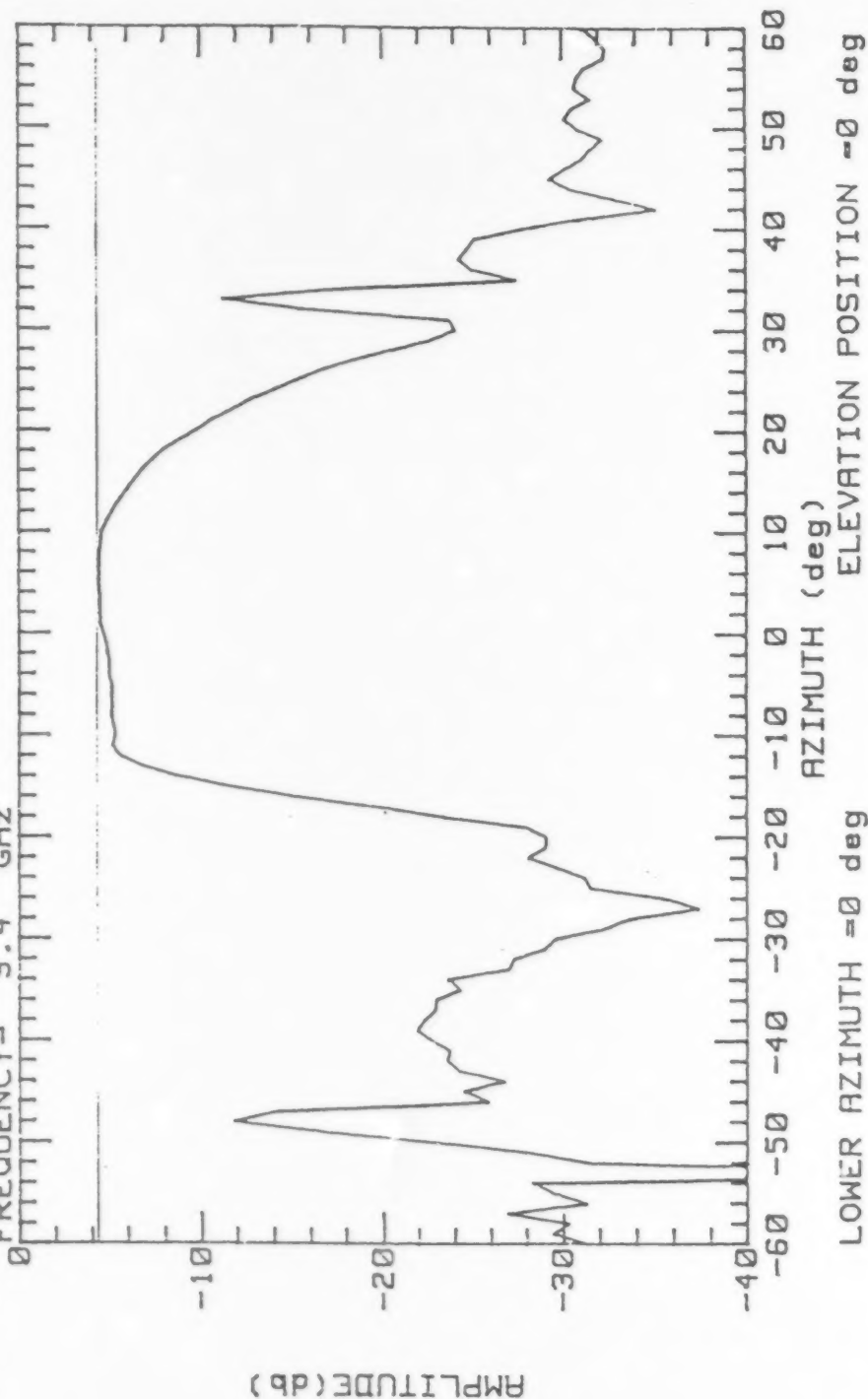
MPB

TECHNOLOGIES INC. Tx.H Rx.V GRID 45.+90 Deg.ABSORBER BETWEEN HORNS

MPB TECHNOLOGIES INC.

CORNER REFLECTOR MPB #1

FREQUENCY= 9.4 GHz



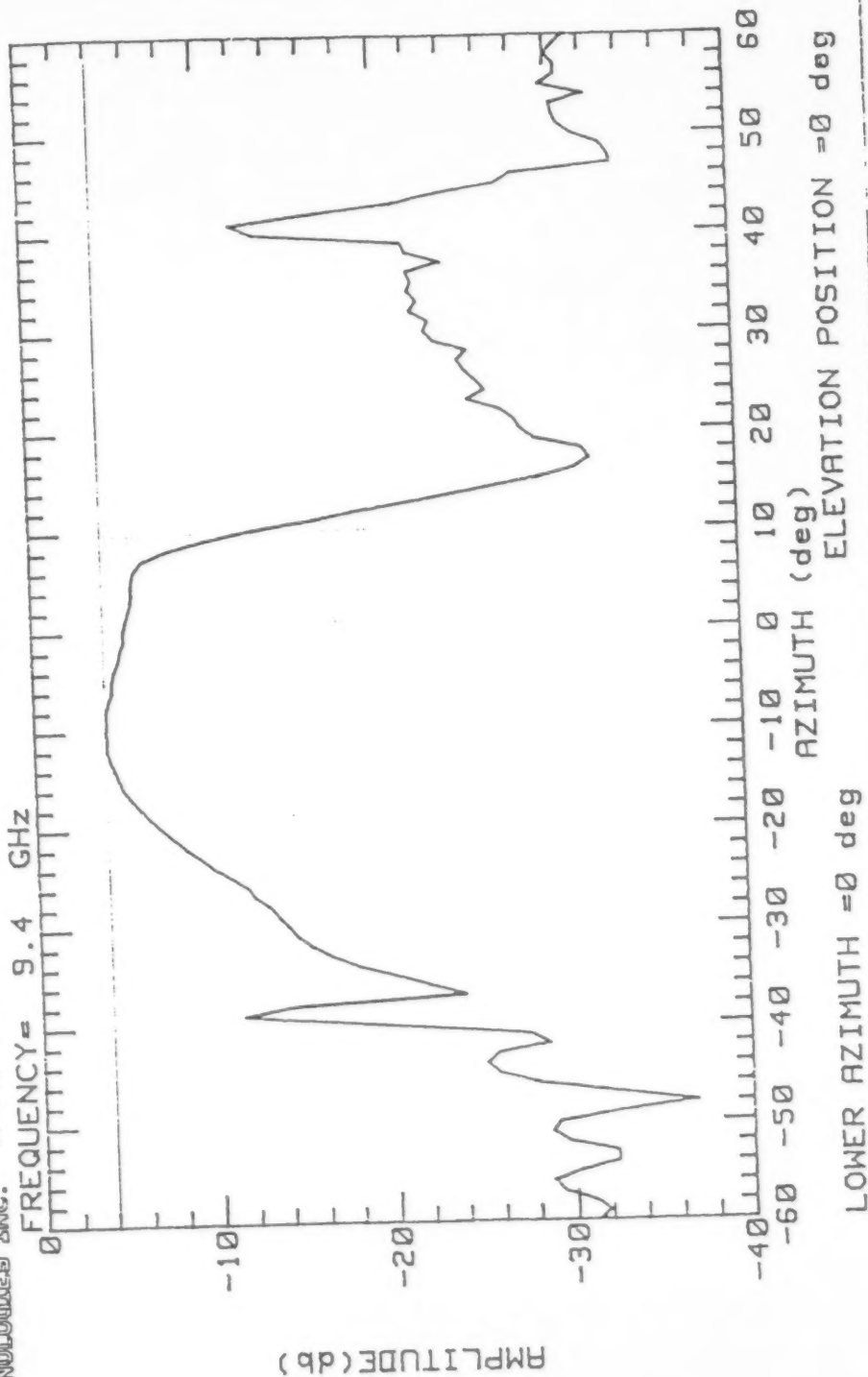
MPB TECHNOLOGIES INC. Exp.108SCAN 1 BY:L. ALLAN

ON 14 Jan 1988 15:40:21



MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #1
Tx.H Rx.V GRID 45.-90 Deg.ABSORBER BETWEEN HORNS

FREQUENCY = 9.4 GHz



LOWER AZIMUTH = 0 deg

AZIMUTH (deg)

ELEVATION POSITION = 0 deg

MPB TECHNOLOGIES INC. Exp.1095SCAN 1 BY:L. ALLAN

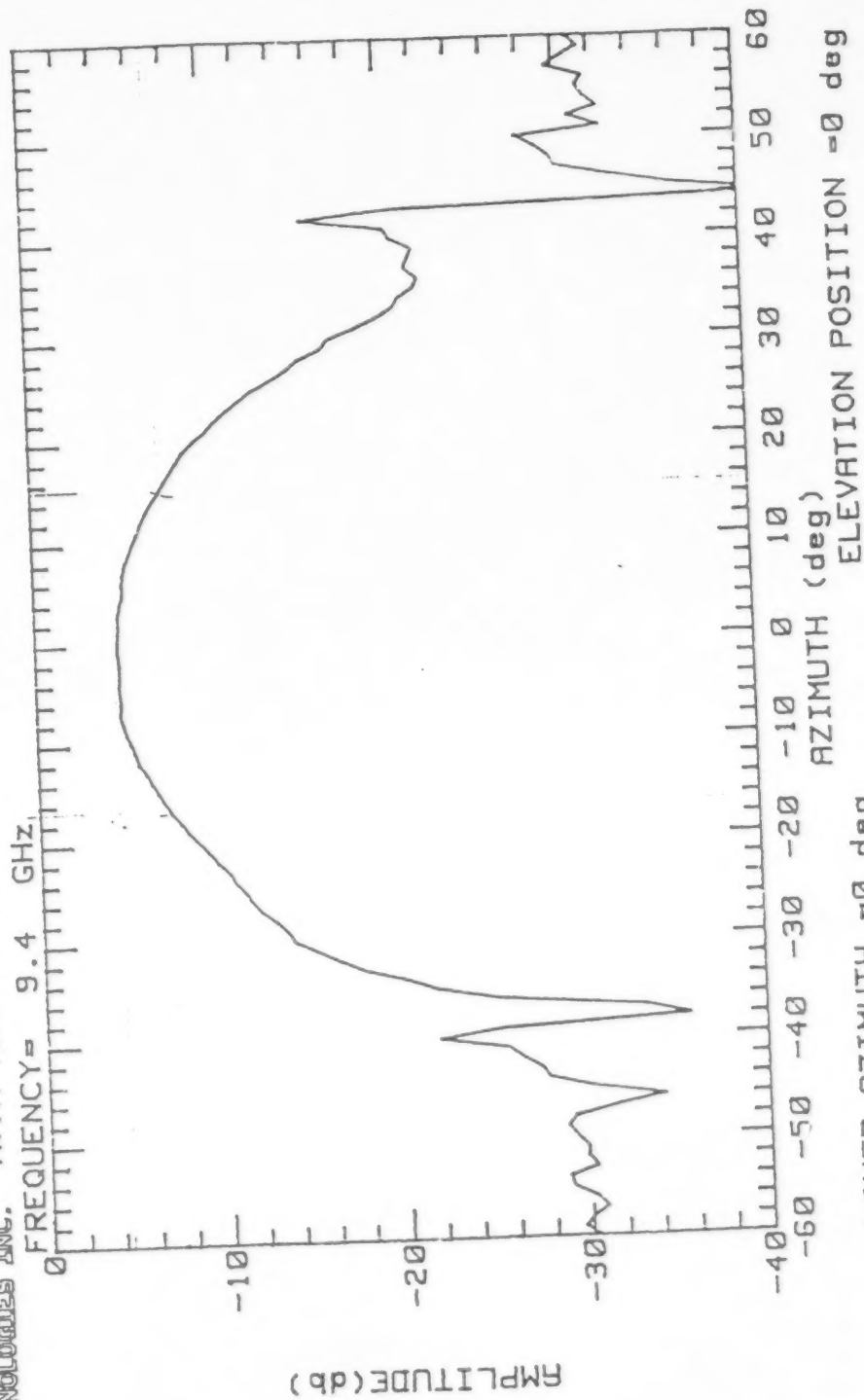
ON 14 Jan 1988 15:46:10

MPB

TECHNOLOGIES INC.

MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #1
Tx. H Rx. V GRID 45. Deg. ABSORBER BETWEEN HORNS

FREQUENCY = 9.4 GHz



MPB TECHNOLOGIES INC. Exp. 110SCAN 1 BY: L. ALLAN

REPEAT of 107

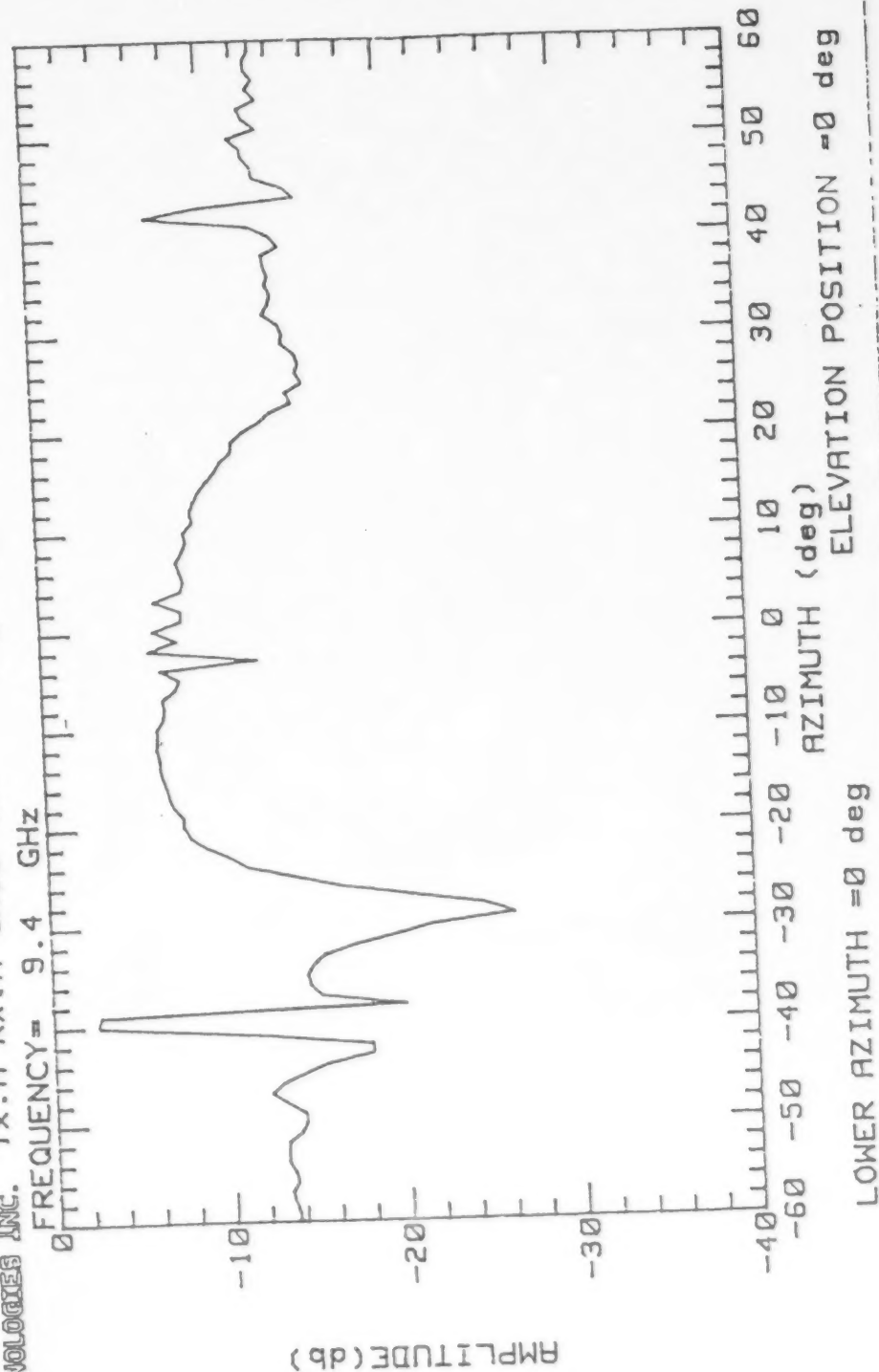
ON 14 Jan 1988 15:55:12



TECHNOLOGIES INC.

MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #1
Tx.H Rx.H GRID 45. Deg.ABSORBER BETWEEN HORNS

FREQUENCY = 9.4 GHz



LOWER AZIMUTH = 0 deg

AZIMUTH (deg)
ELEVATION POSITION = 0 deg

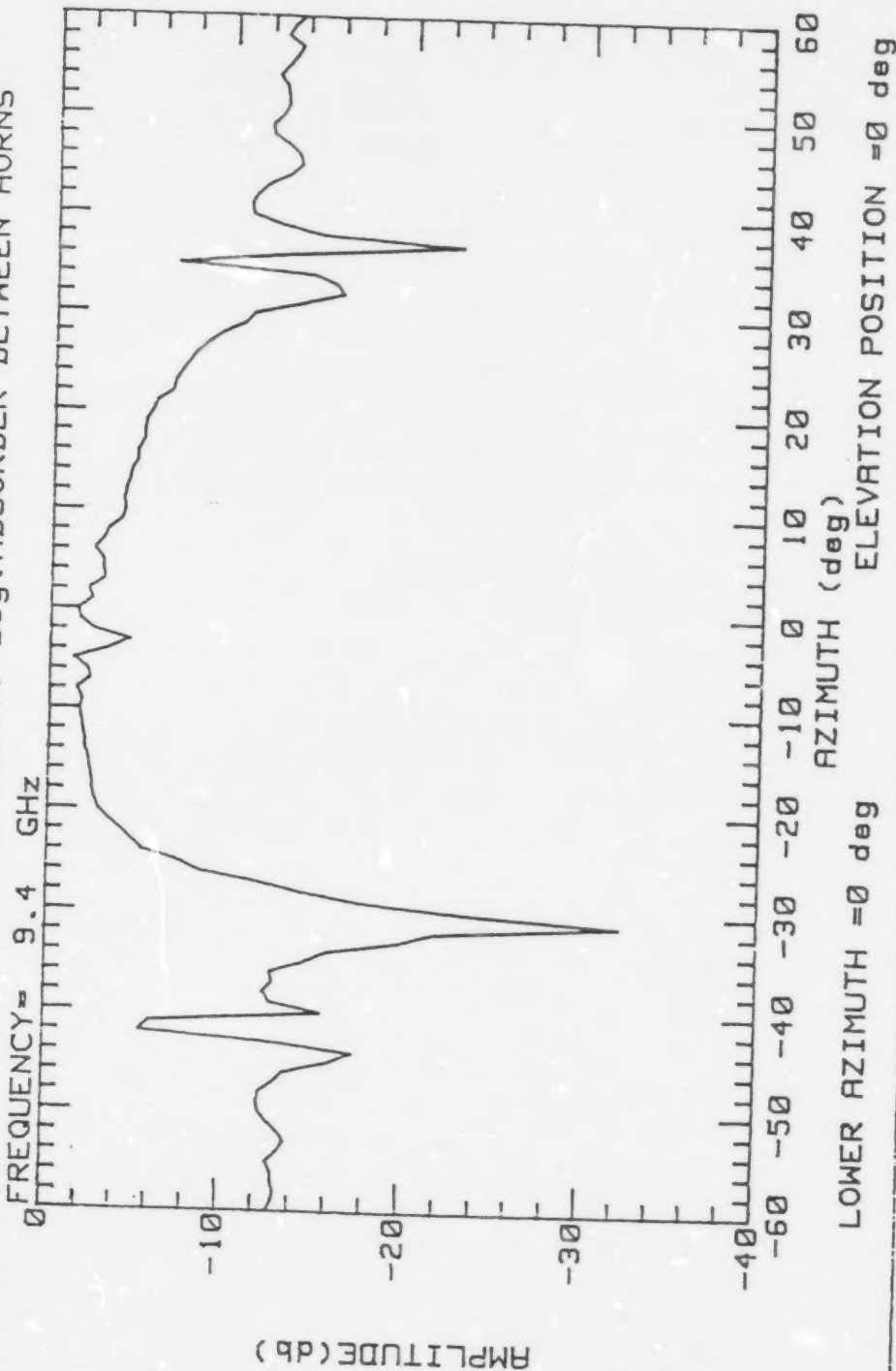
MPB TECHNOLOGIES INC. Exp.111SCAN 1 BY:L. ALLAN

ON 14 Jan 1988 16:00:38

MPB

TECHNOLOGIES INC.

MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #1
Tx.H Rx.H GRID 90.(V) Deg.ABSORBER BETWEEN HORNS
FREQUENCY = 9.4 GHz



MPB TECHNOLOGIES INC. Exp.1125CAN 1 BY:L. ALLAN

ON 14 Jan 1988 16:06:24

REPEAT of 105

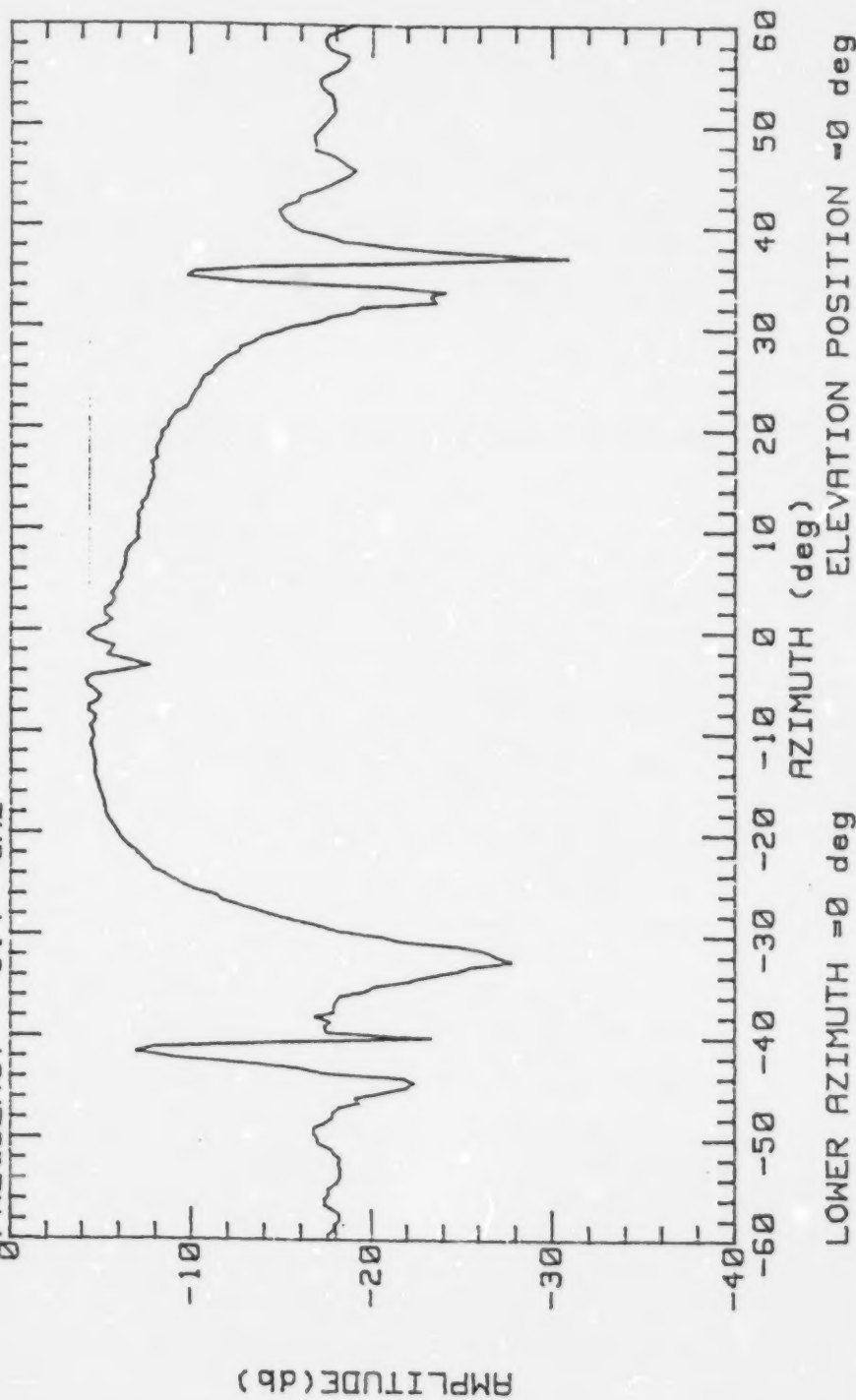
MPA

TECHNOLOGIES INC. Tx.H Rx.H GRID 90.(V) Deg.ABSORBER BETWEEN HORNS

MPB TECHNOLOGIES INC.

CORNER REFLECTOR MPB #1

FREQUENCY= 9.4 GHz



MPB TECHNOLOGIES INC. Exp.118SCAN 1 BY:L. ALLAN

ON 15 Jan 1988 13:13:56

REPEAT of 105 of Previous Day (Jan 14)

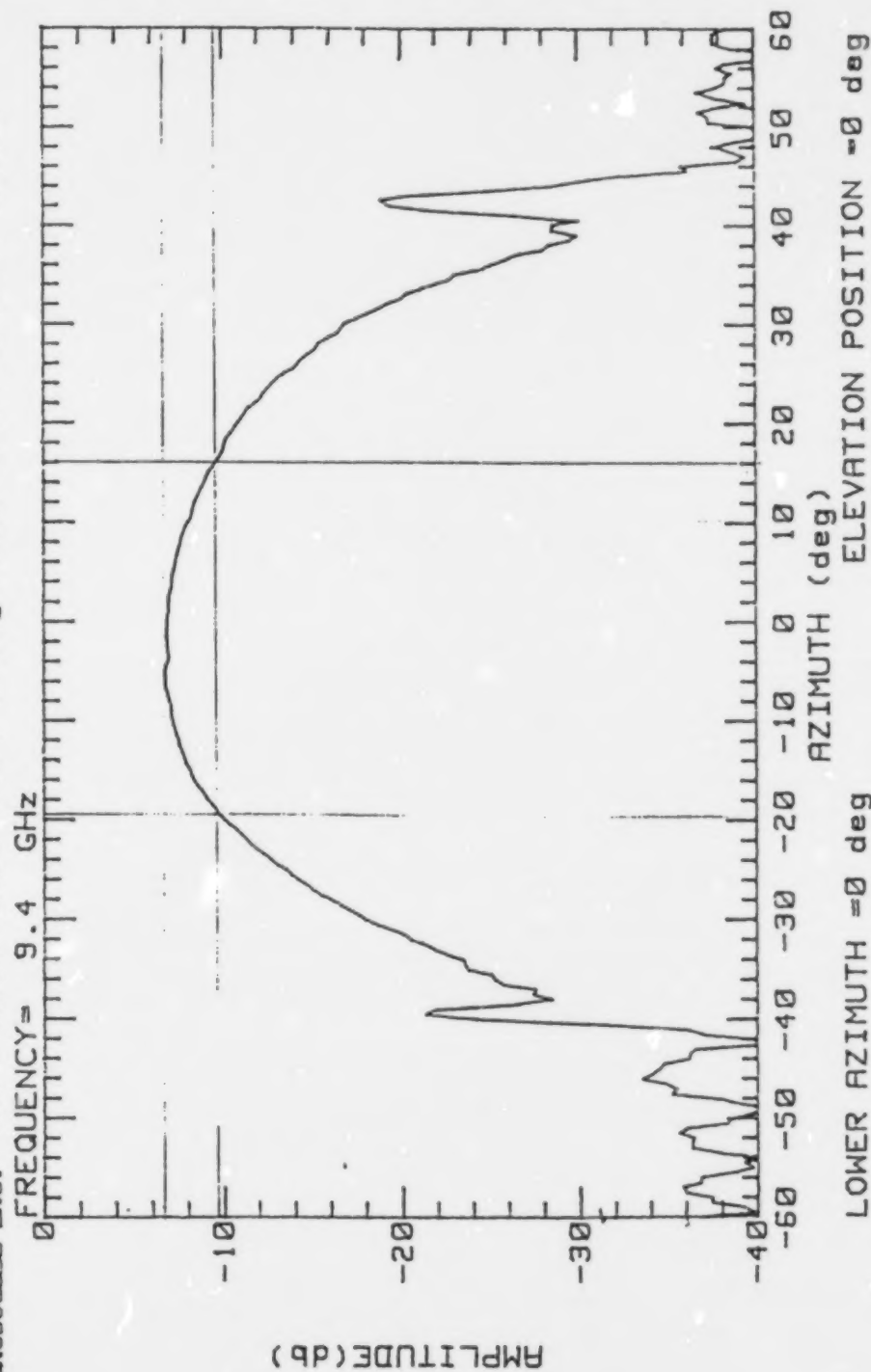


MPB TECHNOLOGIES INC. Tx.H Rx.V GRID 45.() Deg.ABSORBER BETWEEN HORNS

MPB TECHNOLOGIES INC.

CORNER REFLECTOR MPB #1

0 FREQUENCY= 9.4 GHz



MPB TECHNOLOGIES INC. Exp. 120SCAN 1 BY: L. ALLAN

ON 15 Jan 1988 13:32:12

REPORT of 1079110 of PREVIOUS DAY (Jan 14)

MPB

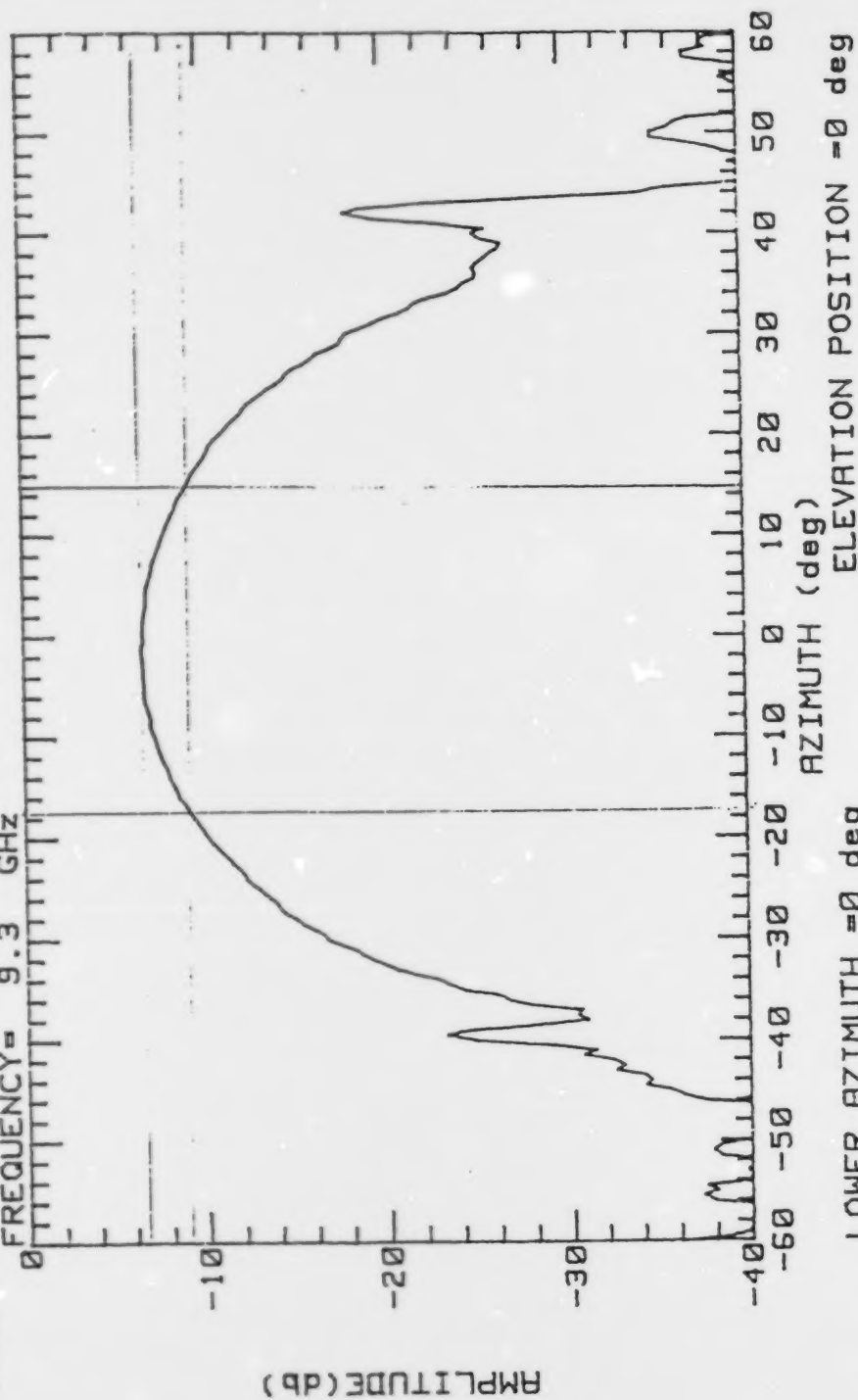
TECHNOLOGIES INC.

MPB TECHNOLOGIES INC.

CORNER REFLECTOR MPB #1

Tx.H Rx.V GRID 45.() Deg.ABSORBER BETWEEN HORNS

FREQUENCY= 9.3 GHz

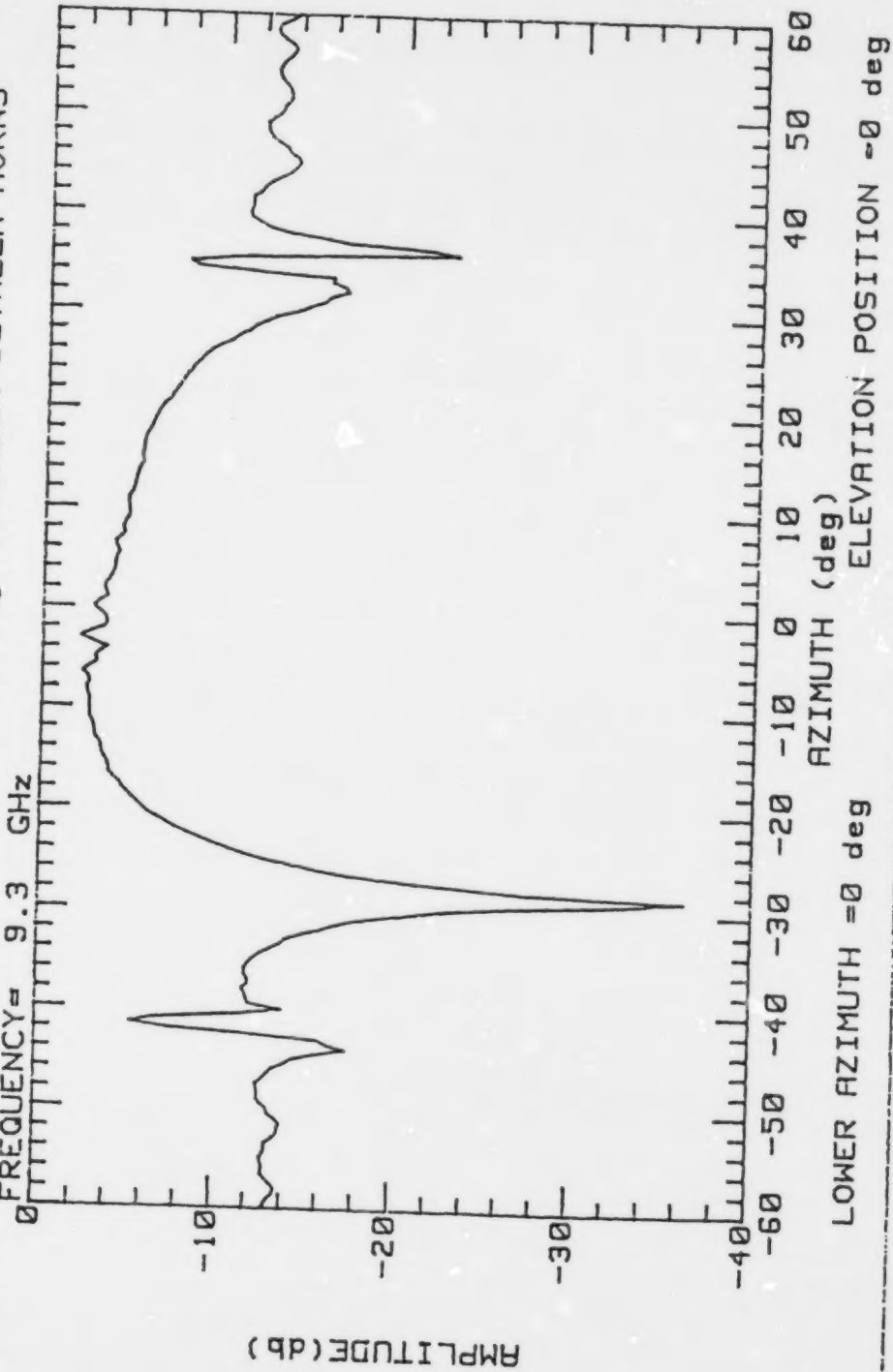


ON 15 Jan 1988 14:20:07

MPB TECHNOLOGIES INC. Exp.121SCAN 1 BY:L. ALLAN



MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #1
Tx.H Rx.H GRID 90.(V) Deg.ABSORBER BETWEEN HORNS
FREQUENCY= 9.3 GHz



MPB TECHNOLOGIES INC. Exp.122SCAN 1 BY:L. ALLAN

ON 15 Jan 1988 14:29:33

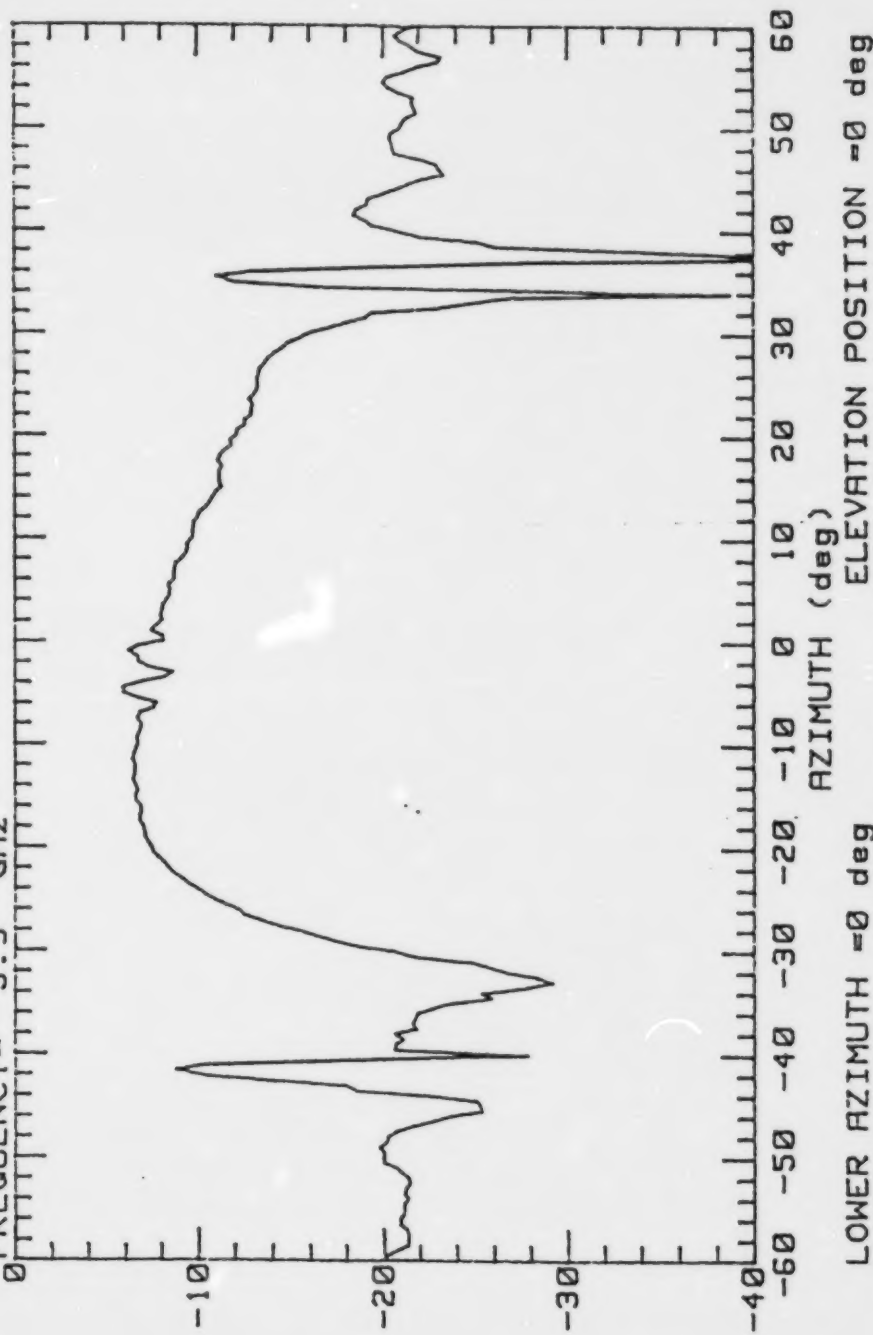


MPB TECHNOLOGIES INC. Tx.H Rx.H GRID 90.(V) Deg.ABSORBER BETWEEN HORNS

MPB TECHNOLOGIES INC.

CORNER REFLECTOR MPB #1

FREQUENCY= 9.5 GHz



MPB TECHNOLOGIES INC. Exp.1235CAN 1 BY:L. ALLAN

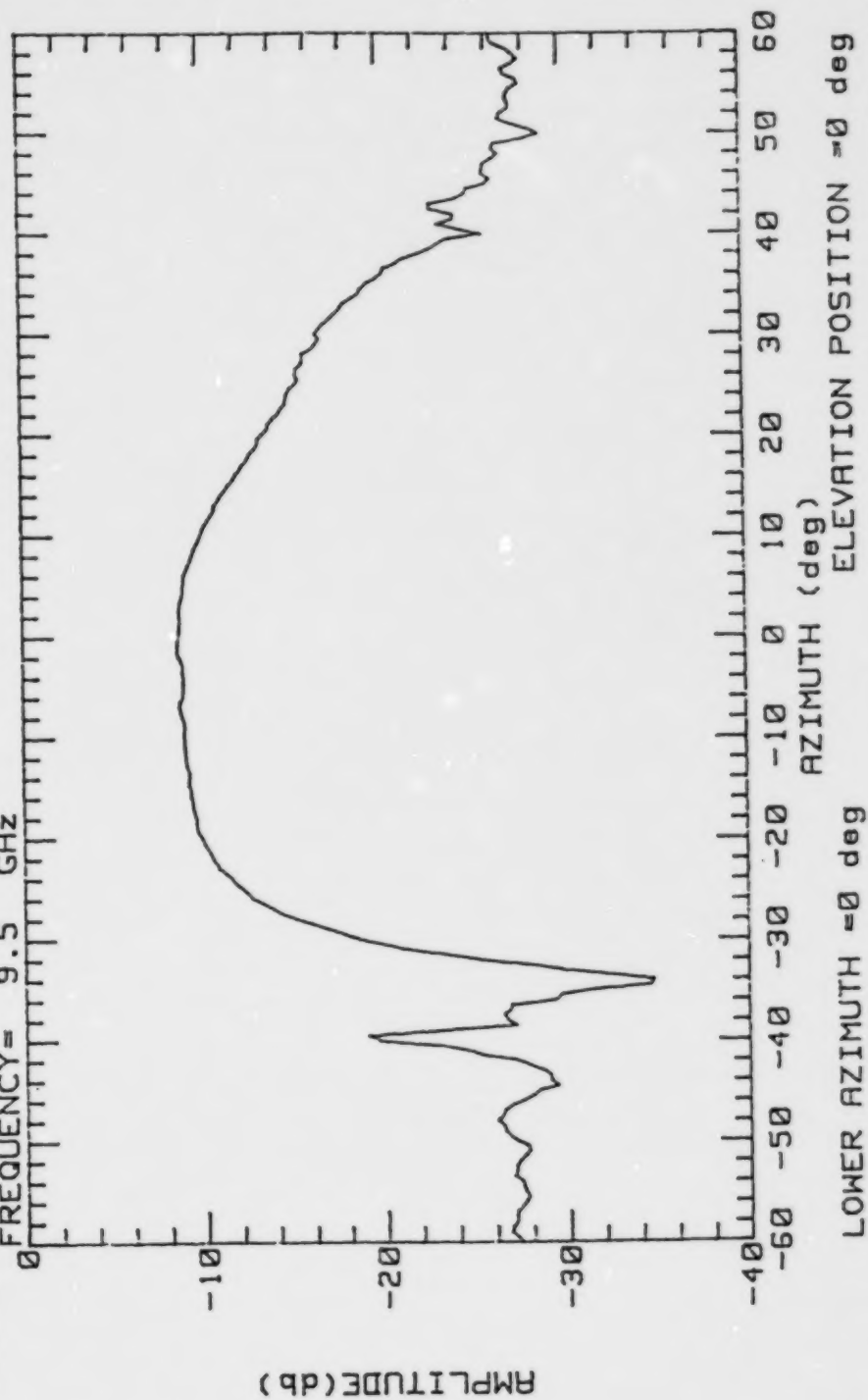
ON 15 Jan 1988 14:36:17



MPB TECHNOLOGIES INC. Tx.H Rx.V GRID 45.() Deg.ABSORBER BETWEEN HORNS

CORNER REFLECTOR MPB #1

FREQUENCY= 9.5 GHz

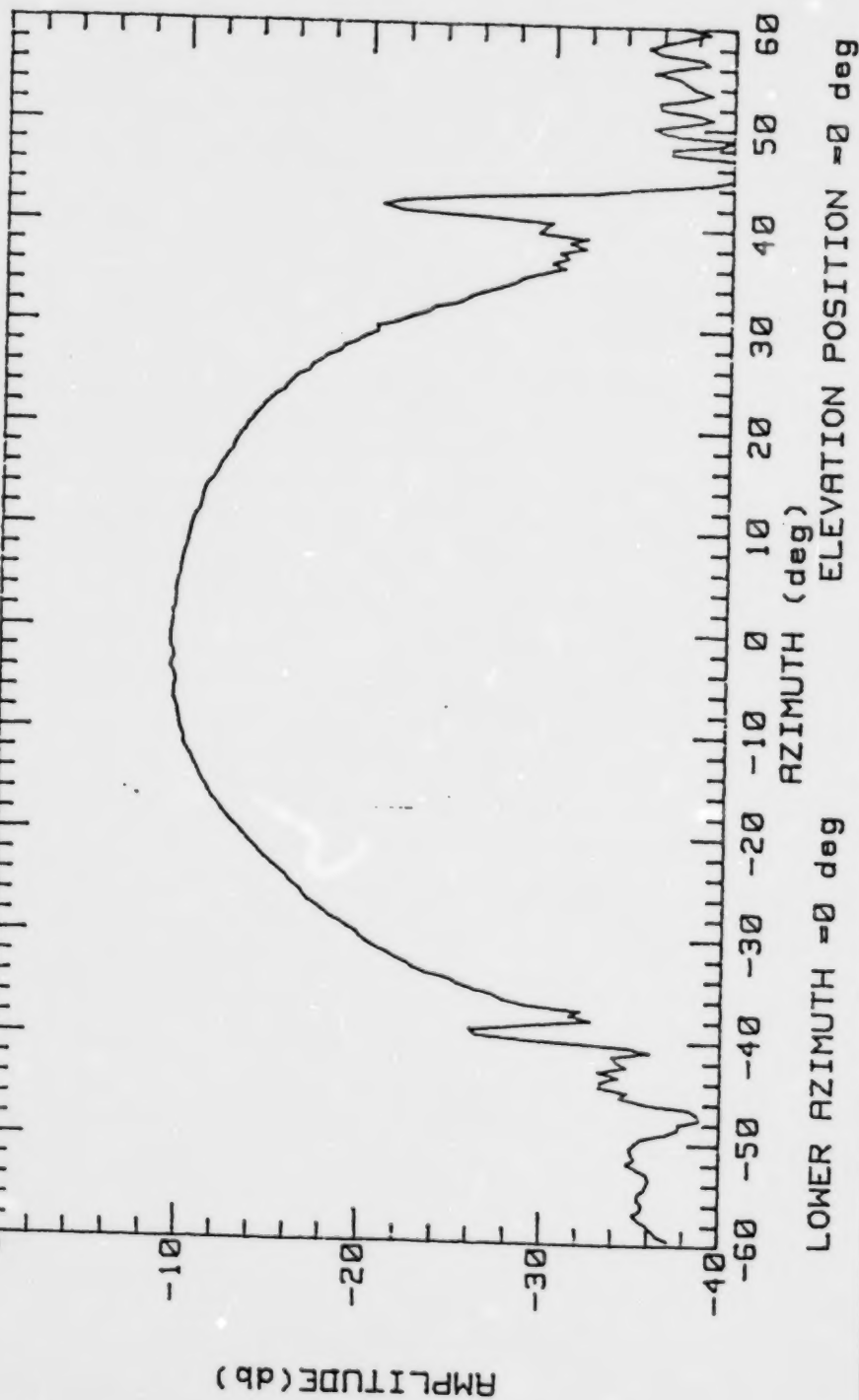


MPB TECHNOLOGIES INC. Exp.124SCAN 1 BY:L. ALLAN

ON 15 Jan 1988 14:50:11



MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #1
Tx.H Rx.V GRID 45.() Deg.ABSORBER BETWEEN HORNS
FREQUENCY= 9.6 GHz



MPB TECHNOLOGIES INC. Exp.125SCAN 1 BY:L. ALLAN

ON 15 Jan 1988 14:57:45

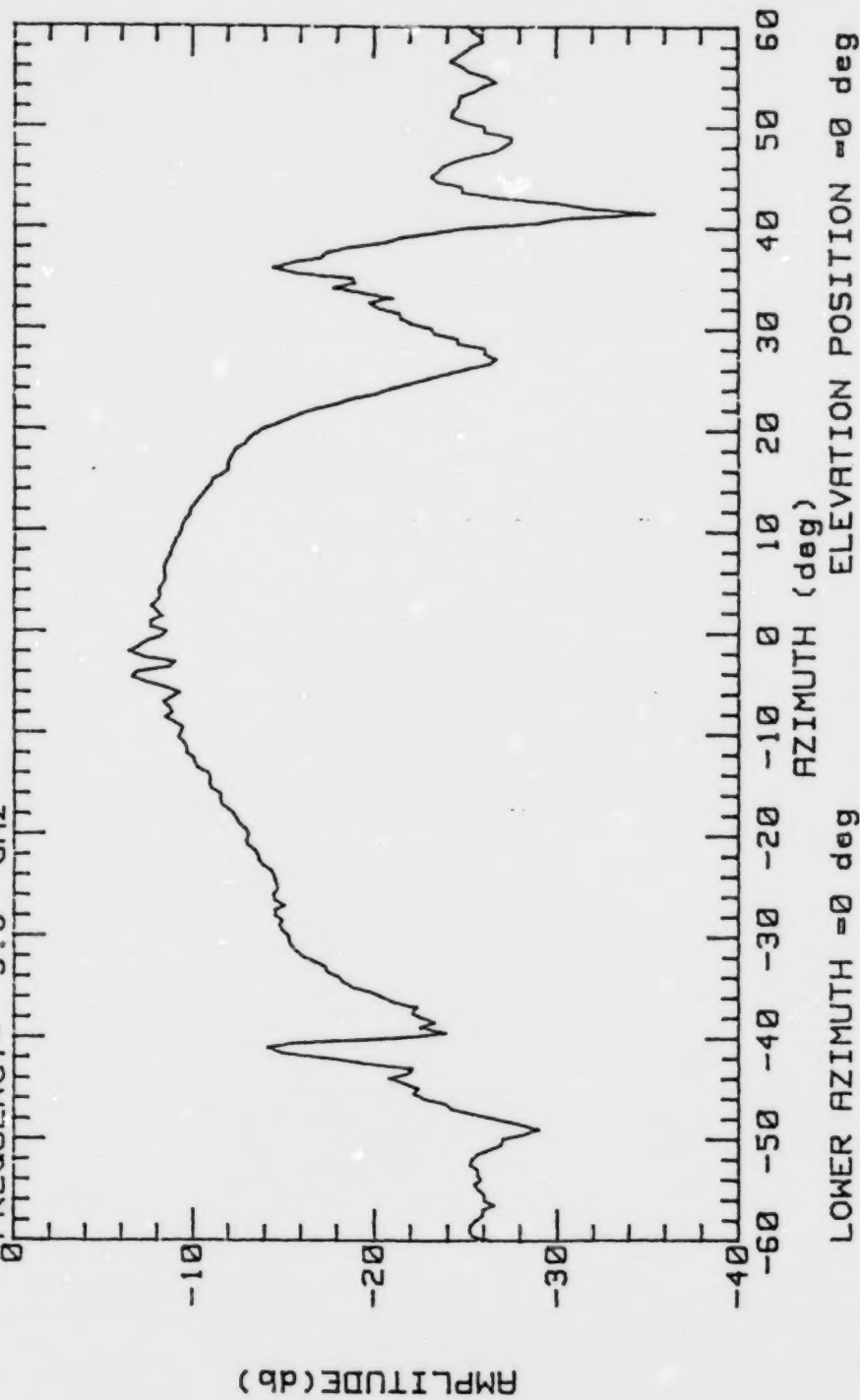
MRA

TECHNOLOGIES INC. Tx.H Rx.H GRID 90.(V) Deg.ABSORBER BETWEEN HORNS

MPB TECHNOLOGIES INC.

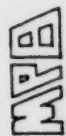
CORNER REFLECTOR MPB #1

FREQUENCY = 9.6 GHz



MPB TECHNOLOGIES INC. Exp.126SCAN 1 BY:L. ALLAN

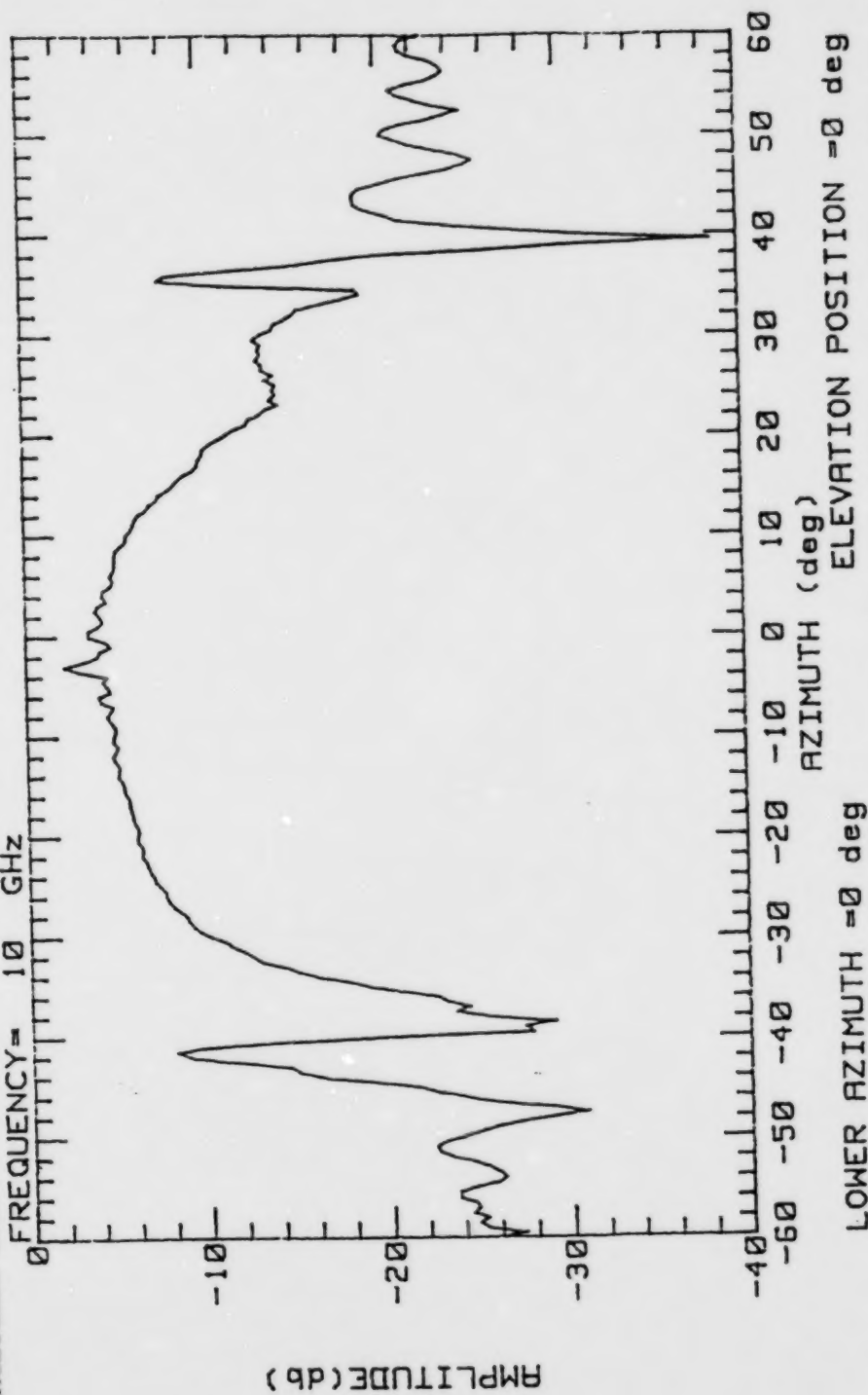
ON 15 Jan 1988 15:05:19



TECHNOLOGIES INC.

MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #1
Tx.H Rx.H GRID 90.(V) Deg.ABSORBER BETWEEN HORNS

FREQUENCY= 10 GHz



LOWER AZIMUTH =0 deg

AZIMUTH (deg)

ELEVATION POSITION =0 deg

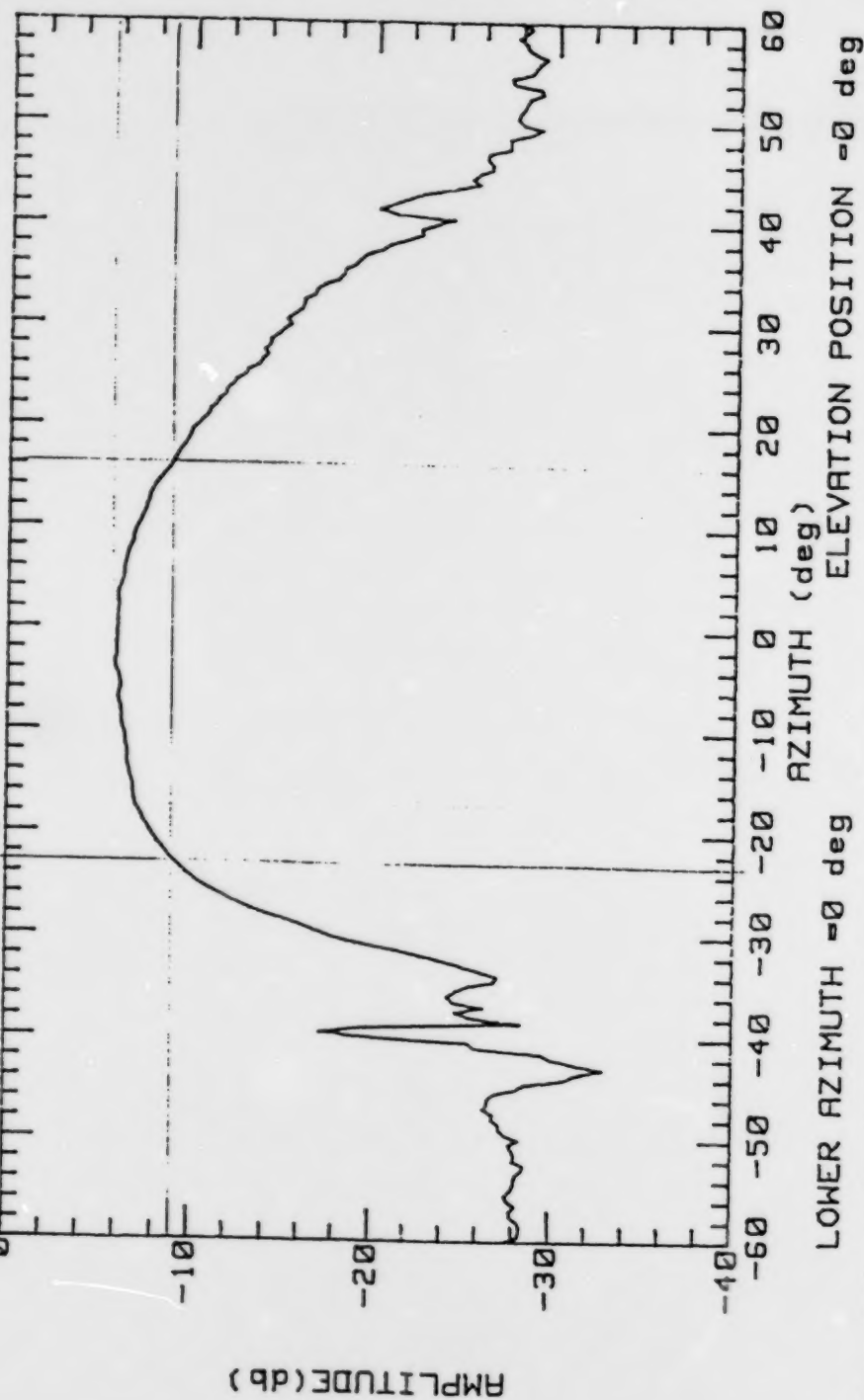
MPB TECHNOLOGIES INC. Exp.127SCAN 1 BY:L. ALLAN

ON 15 Jan 1988 15:36:51



MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #1
Tx.H Rx.V GRID 45.() Deg.ABSORBER BETWEEN HORNS

FREQUENCY= 10 GHz



MPB TECHNOLOGIES INC. Exp.128SCAN 1 BY:L. ALLAN

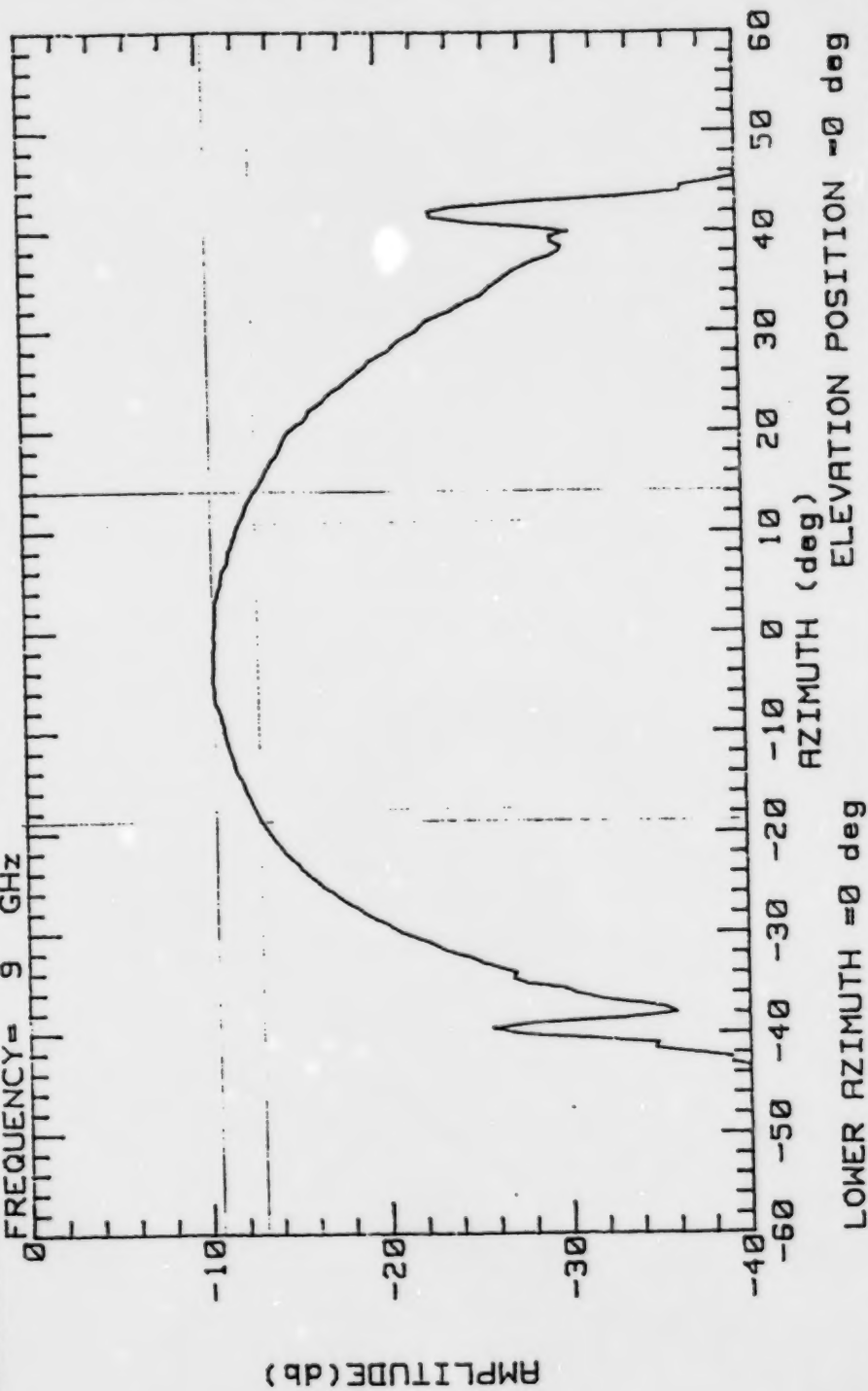
ON 15 Jan 1988 15:48:28

MPB

TECHNOLOGIES INC.

MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #1
Tx.H Rx.V GRID 45.() Deg. ABSORBER BETWEEN HORNS

FREQUENCY = 9 GHz

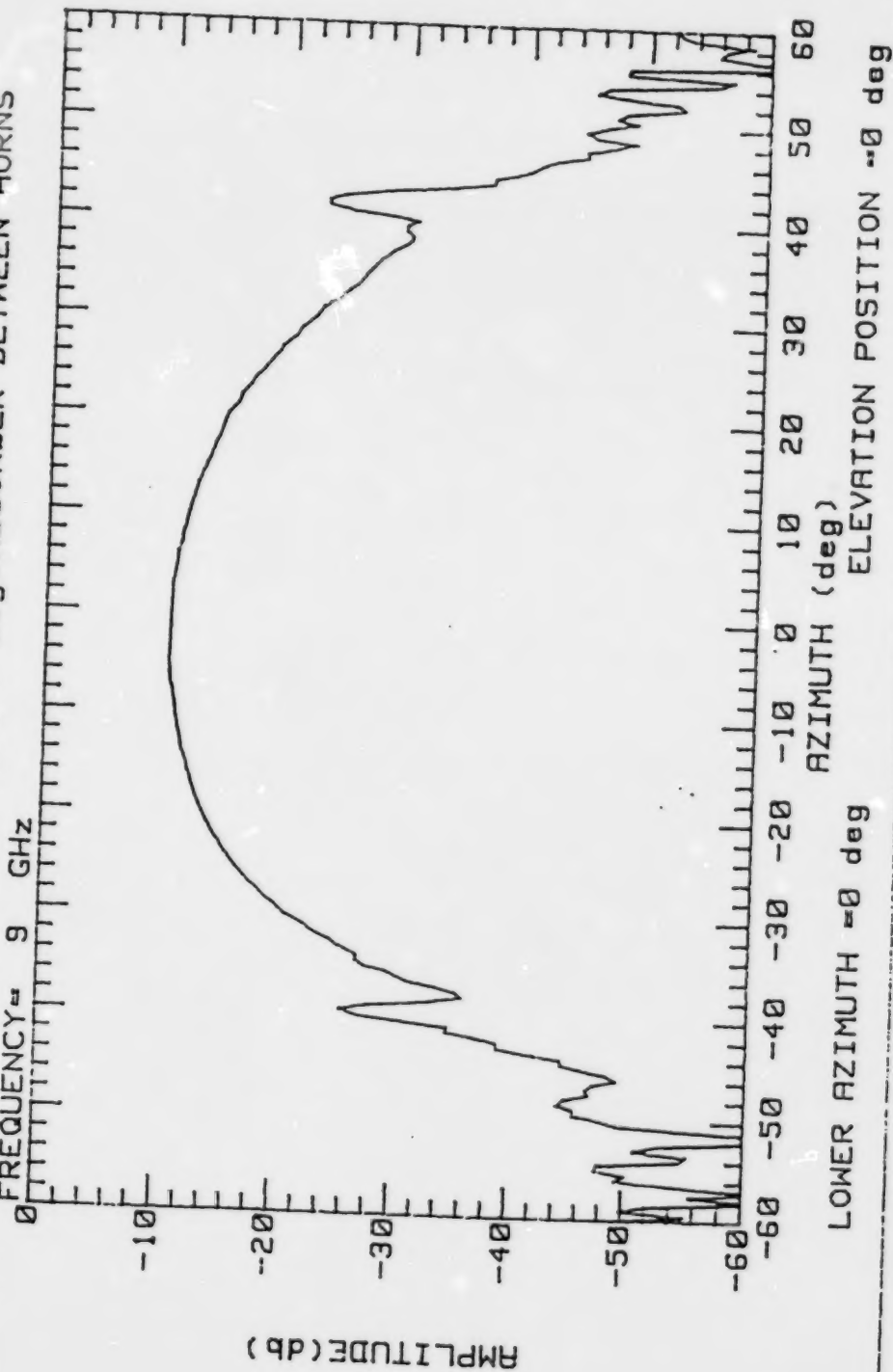


MPB TECHNOLOGIES INC. Exp. 129SCAN 1 BY: L. ALLAN

ON 15 Jan 1988 16:23:13



MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #1
Tx.H Rx.V GRID 45.() Deg.ABSORBER BETWEEN HORNS
FREQUENCY= 9 GHz



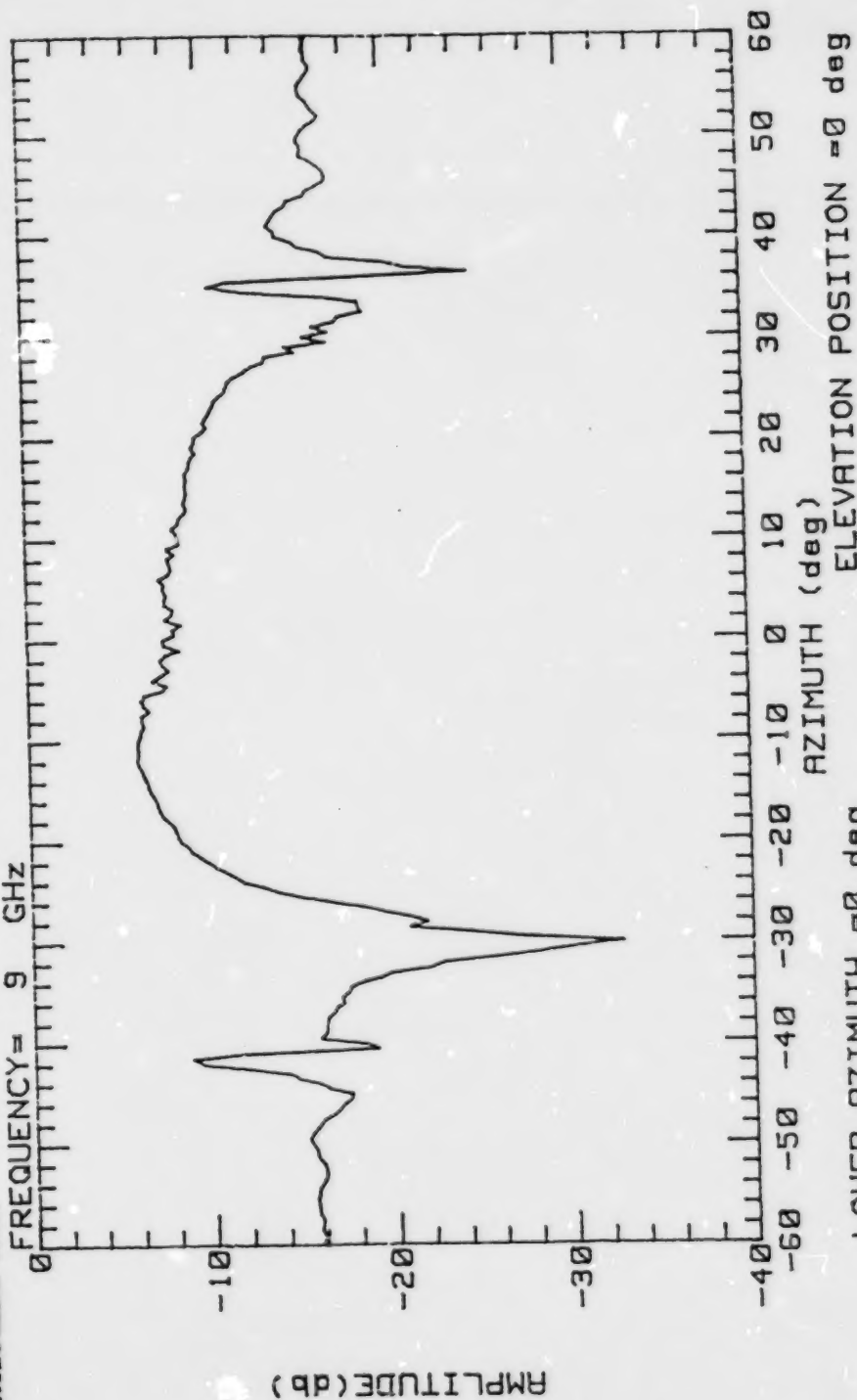
MPB TECHNOLOGIES INC. Exp.1295CAN 1 BY:L. ALLAN

ON 15 Jan 1988 16:23:13



MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #1
Tx.H Rx.H GRID 90.(V) Deg.ABSORBER BETWEEN HORNS

FREQUENCY= 9 GHz



MPB TECHNOLOGIES INC. Exp.130SCAN 1 BY:L. ALLAN

ON 15 Jan 1988 16:29:35

OUTDOOR WINTER ROOM: 11/1/1919

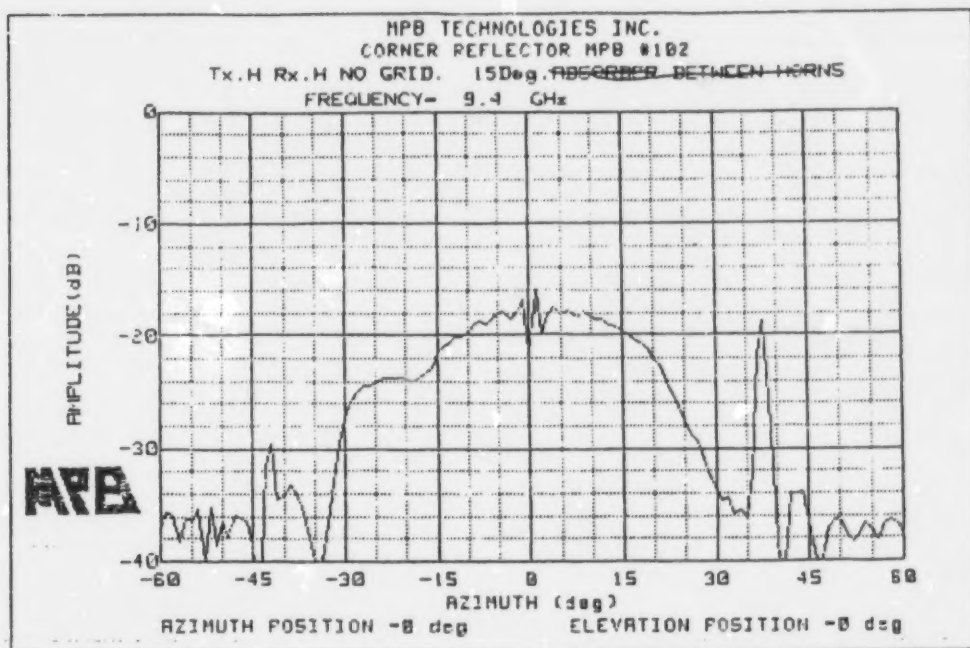


04 22 Feb



ON 22 Feb

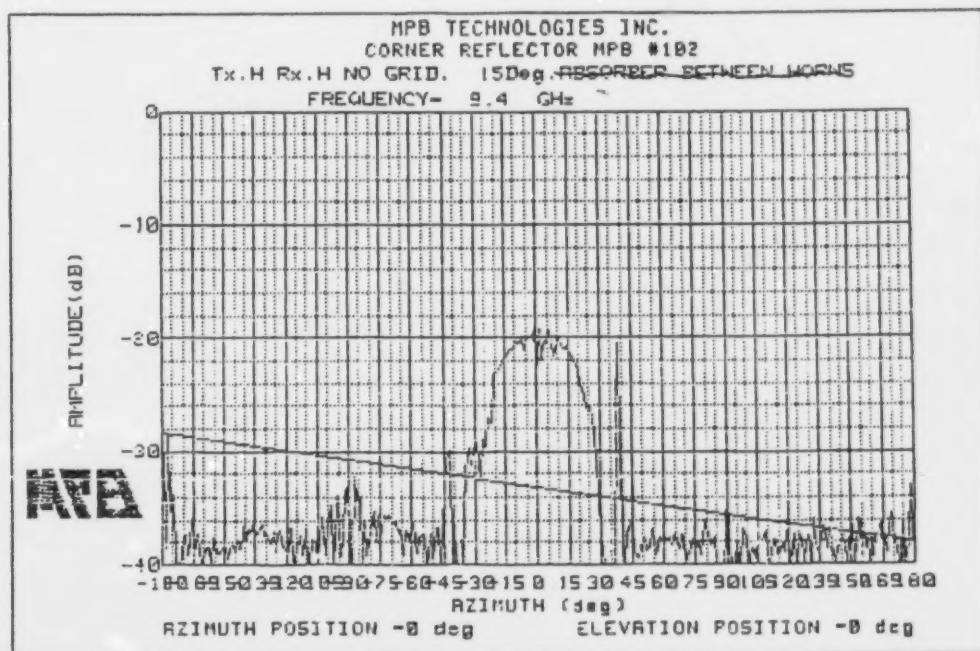
REFL 150° NO GRID



MPB TECHNOLOGIES INC. Exp. 142 SCAN 1 MEASURED BY: B. GIBBS L. ALLAN

ON 22 Feb

REFL. 150°, NO GRID
AZ. $\pm 180^\circ$

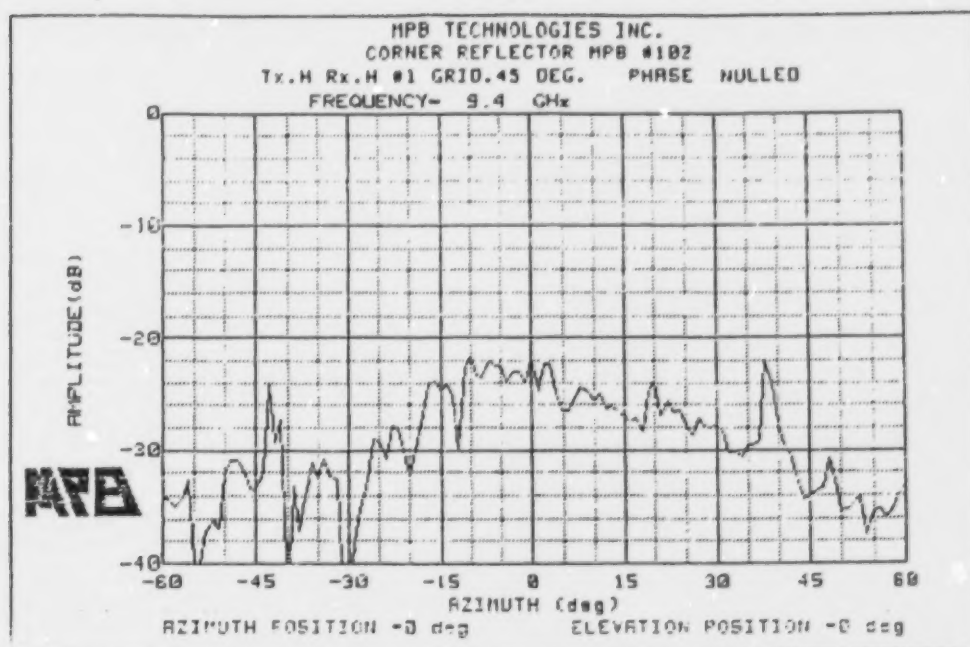


MPB TECHNOLOGIES INC. Exp. 143 SCAN 1 MEASURED BY: B. GIBBS L. ALLAN

ON 22 Feb

GRID No 1. 45°

LIKE

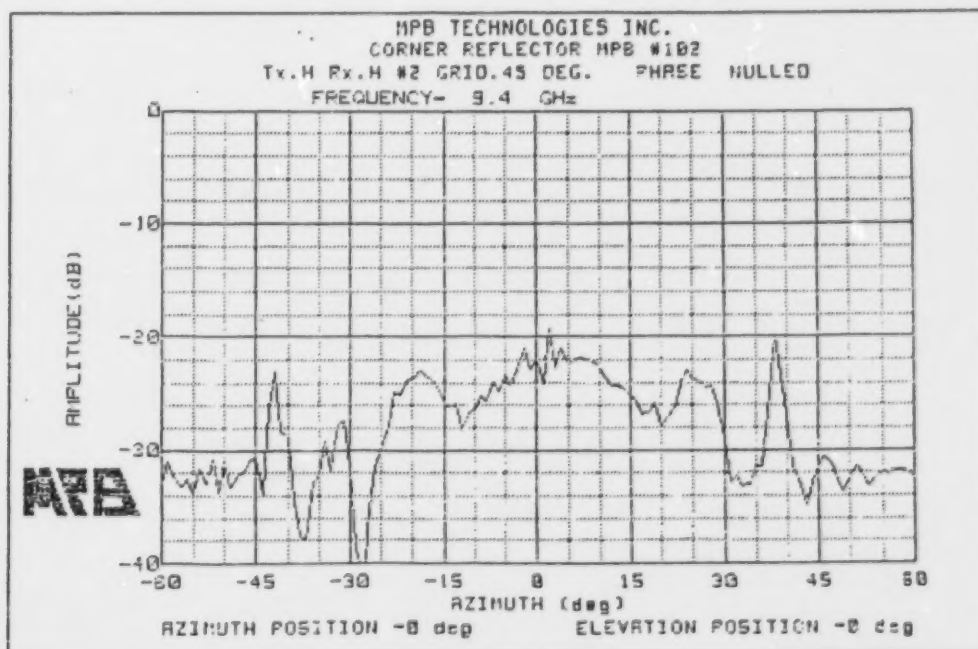


MPB TECHNOLOGIES INC. Exp.144 SCAN 1 MEASURED BY: B. GIBBS L. ALLAN

ON 22 Feb

GRID No 2 45°

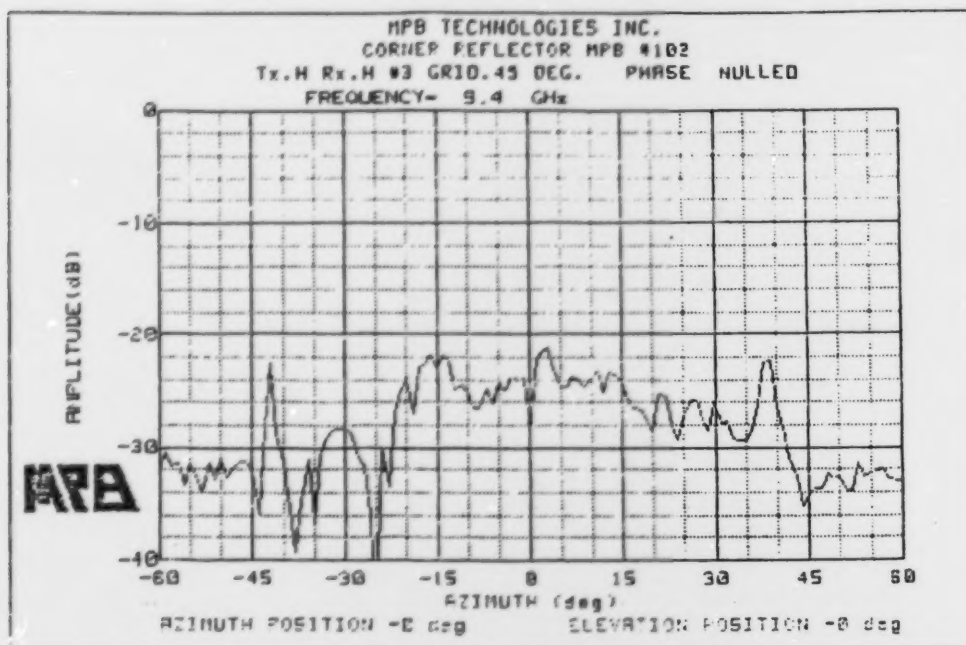
LIKE



MPB TECHNOLOGIES INC. Exp.145 SCAN 1 MEASURED BY: B. GIBBS L. ALLAN

ON 22 Feb

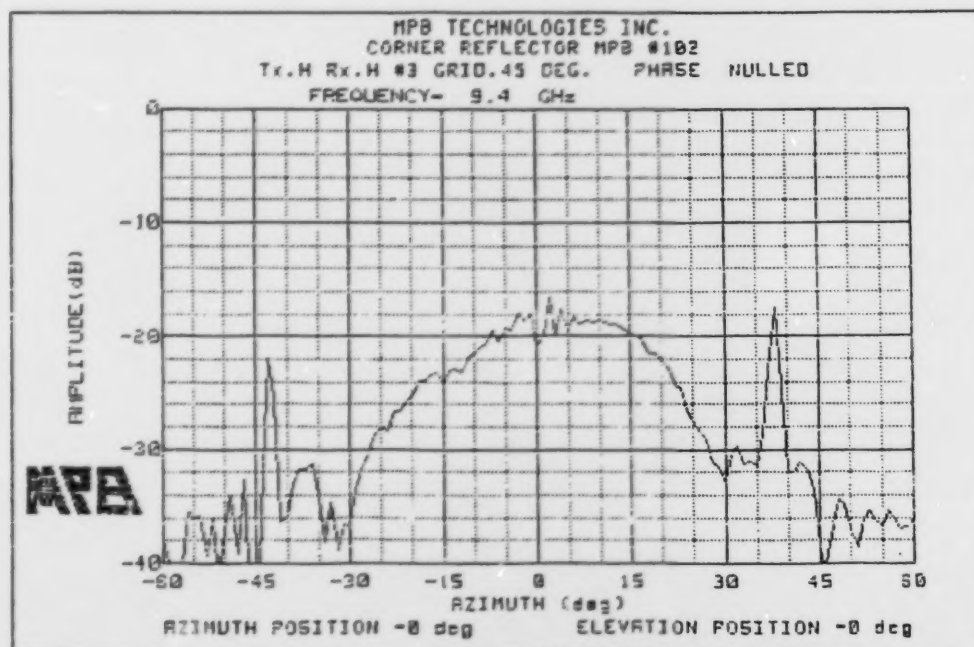
GR L 123, 45°
LIKE



MPB TECHNOLOGIES INC. Exp.145 SCAN 1 MEASURED BY: B. GIBBS L. ALLAN

ON 22 Feb

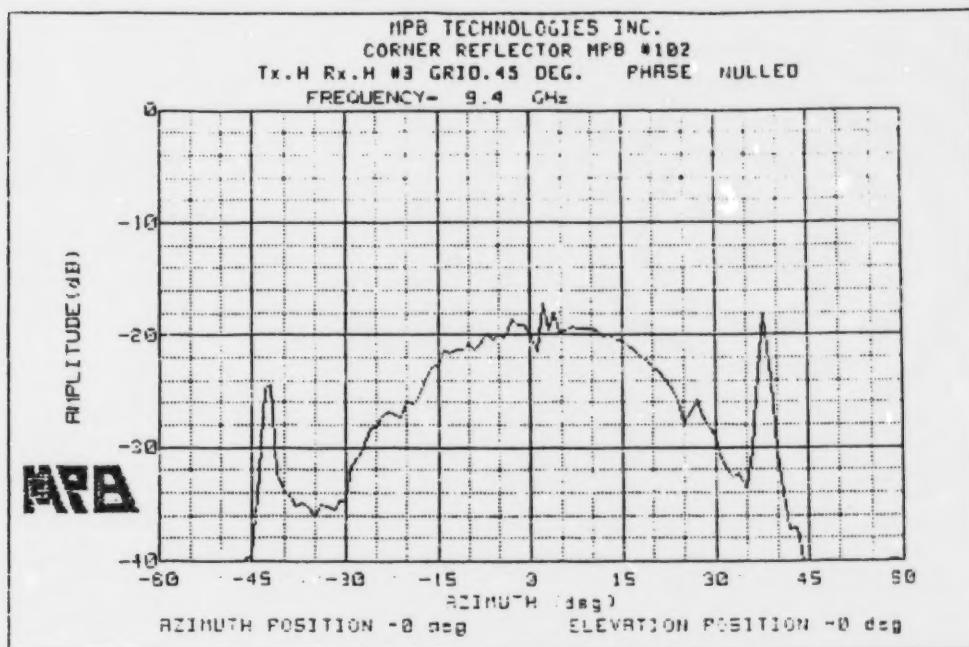
GR L 123, 45° REPEAT AFTER NULL PLACING
LIKE



MPB TECHNOLOGIES INC. Exp.147 SCAN 1 MEASURED BY: B. GIBBS L. ALLAN

ON 22 Feb

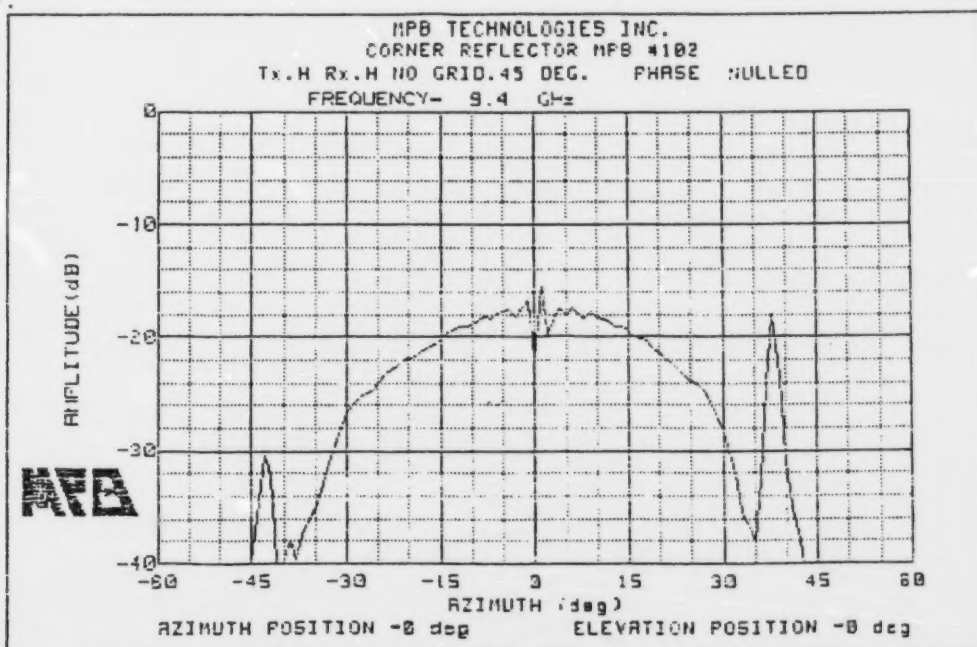
GRID 153, 45°
 LINE



MPB TECHNOLOGIES INC. Exp.148 SCAN 1 MEASURED BY: B. GIBBS L. ALLAN

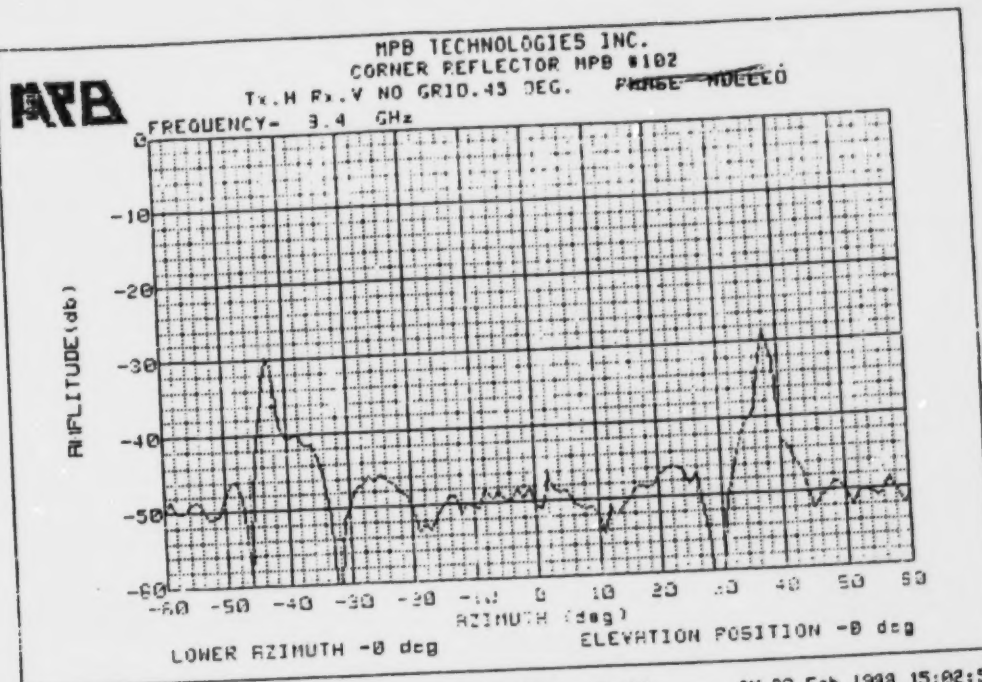
ON 22 Feb

REF. No GRID 15°



MPB TECHNOLOGIES INC. Exp.149 SCAN 1 MEASURED BY: B. GIBBS L. ALLAN

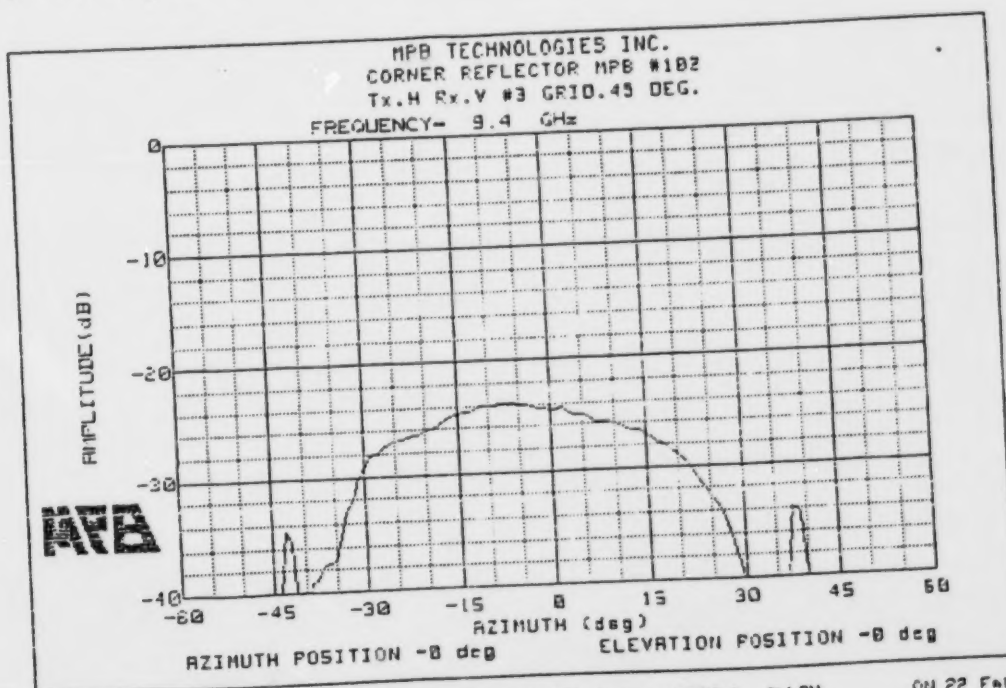
ON 22 Feb



MPB TECHNOLOGIES INC. Exp.150 SCAN 1 BY: B. GIBBS L. ALLAN

ON 22 Feb 1998 15:02:56

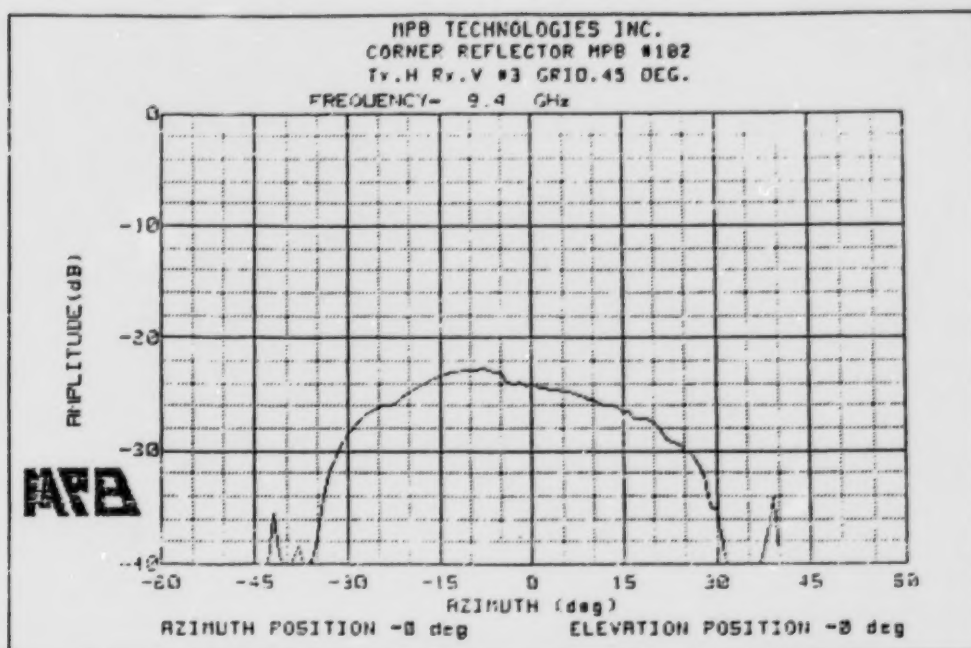
H-V Grid No 3, 45.0°



MPB TECHNOLOGIES INC. Exp.151 SCAN 1 MEASURED BY: B. GIBBS L. ALLAN

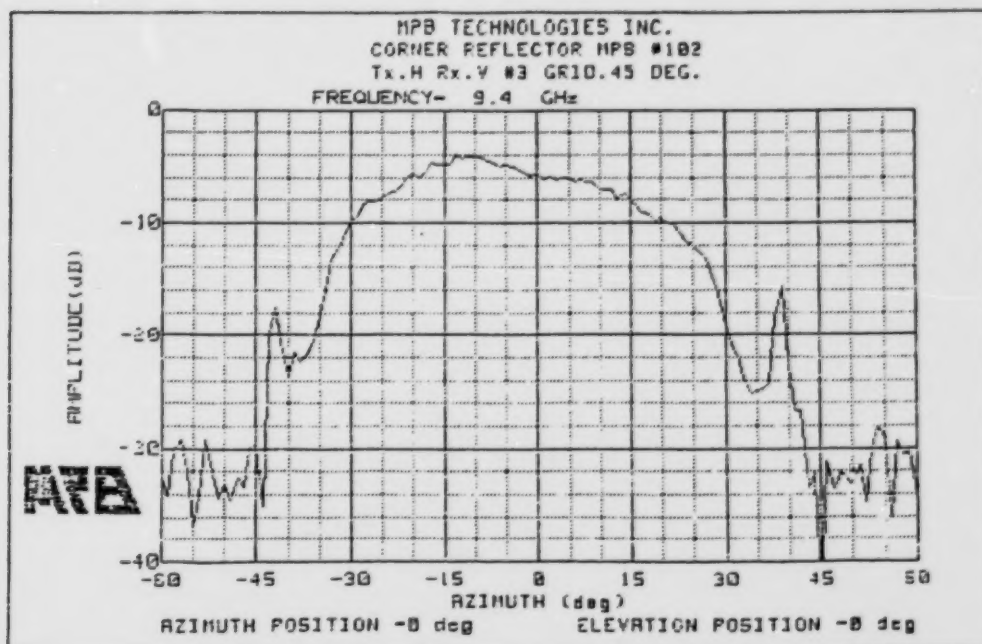
ON 22 Feb

4-0 110.3 44°?

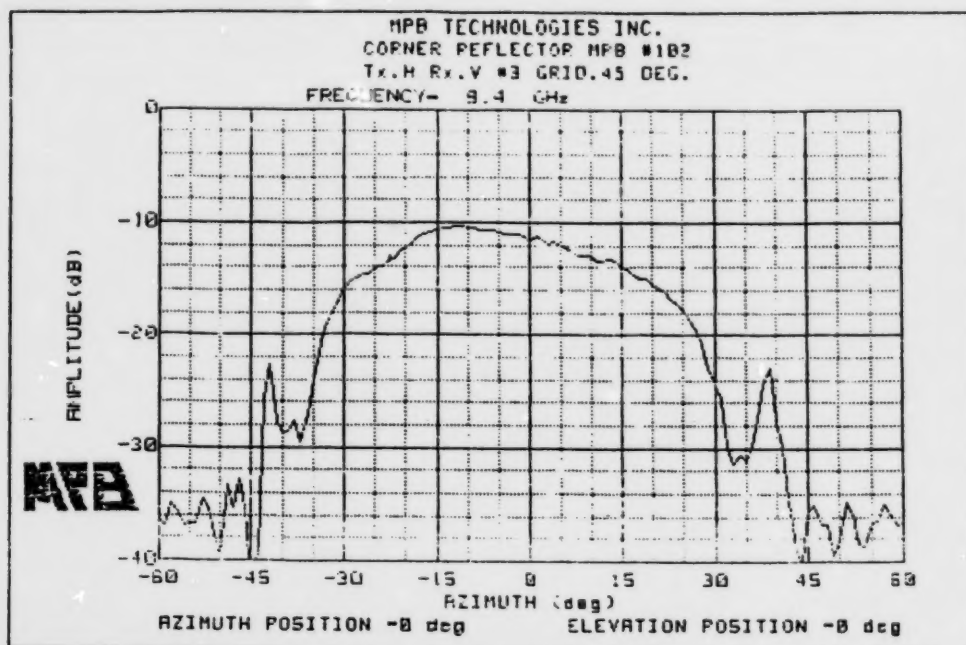


MPB TECHNOLOGIES INC. Exp.152 SCAN 1 MEASURED BY: B. GIBBS L. ALLAN

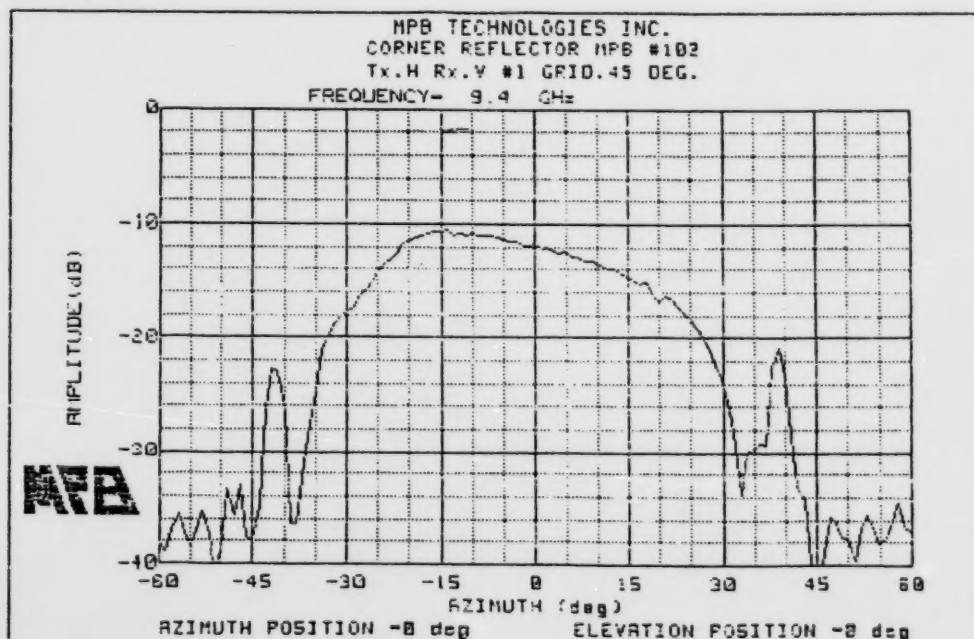
ON 22 Feb

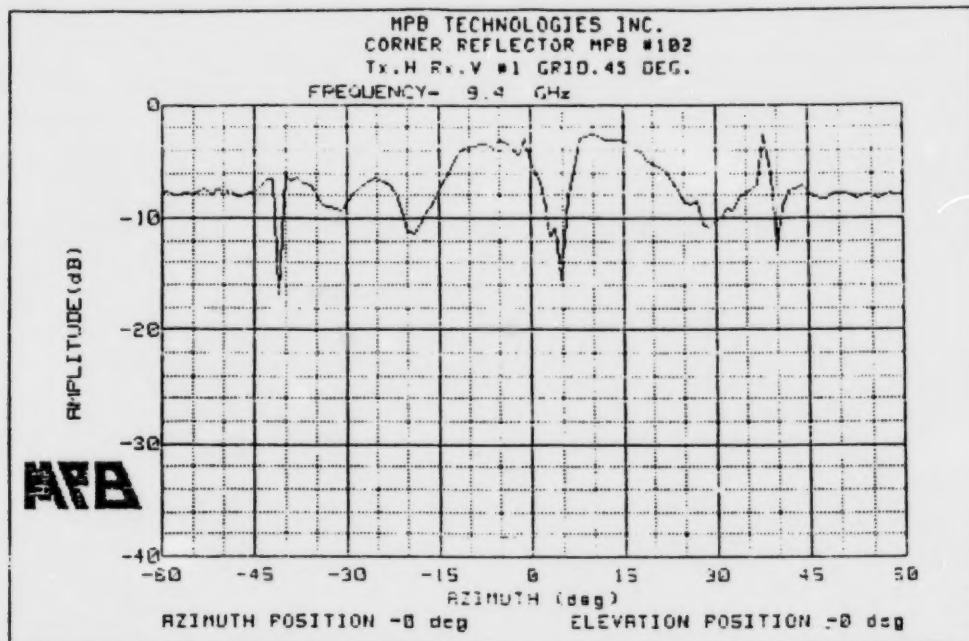


#3 GRID - 1



No 1 Grid 45

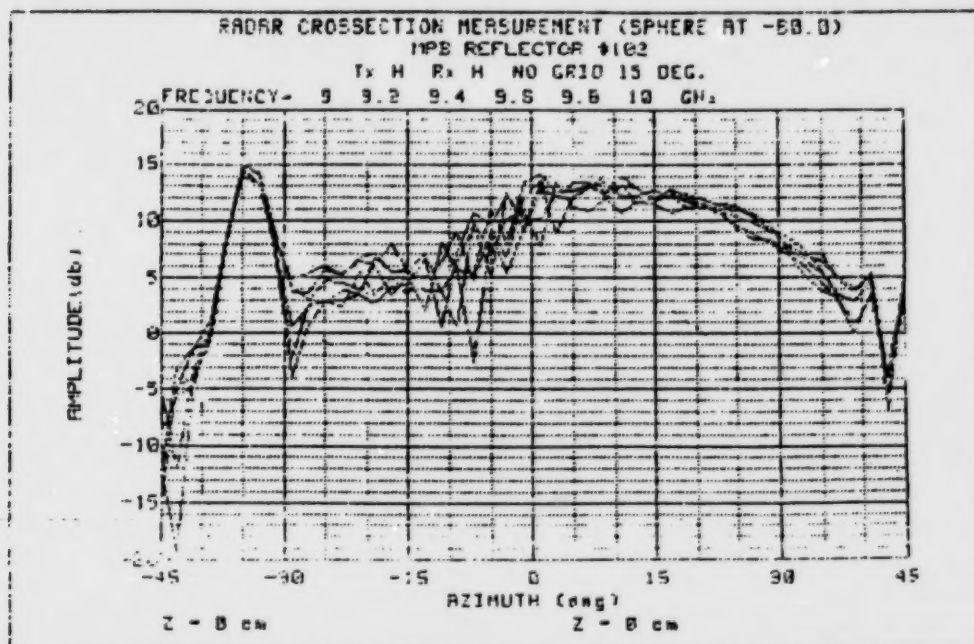




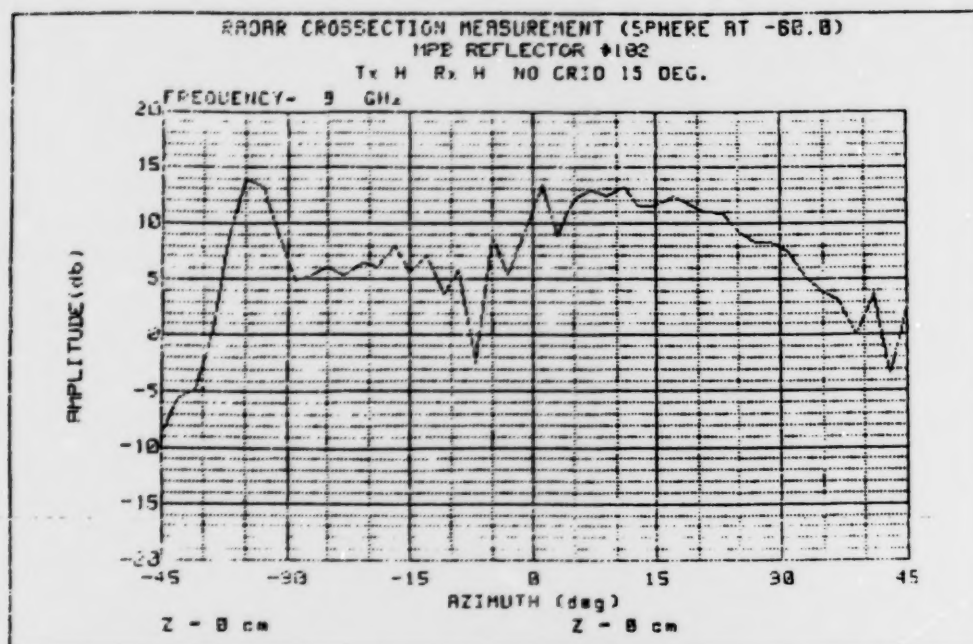
INDOOR ANECHOIC CHAMBER.

III

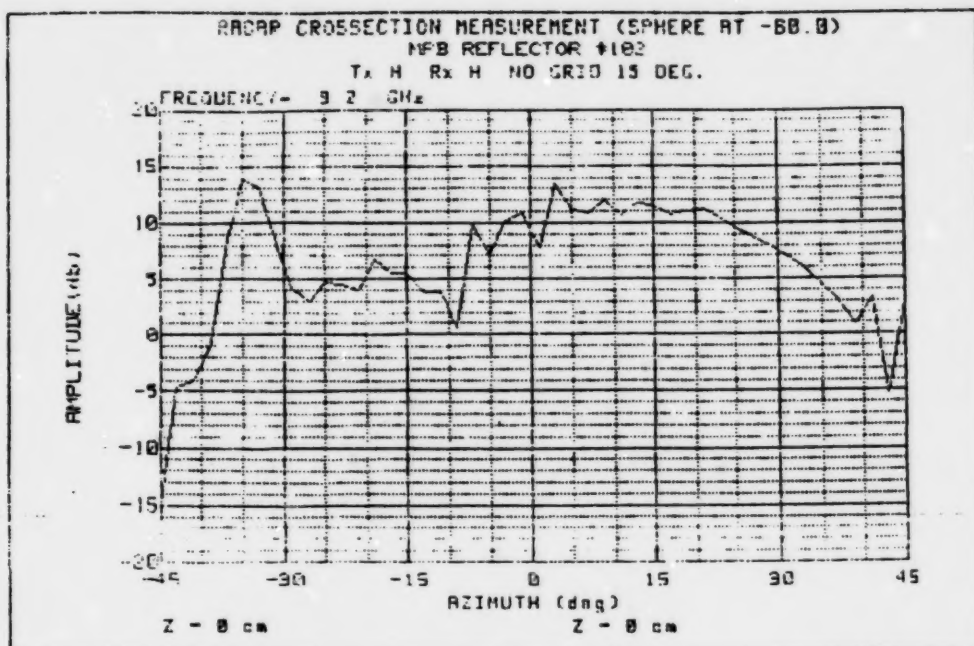
LIKE - NO GRID.



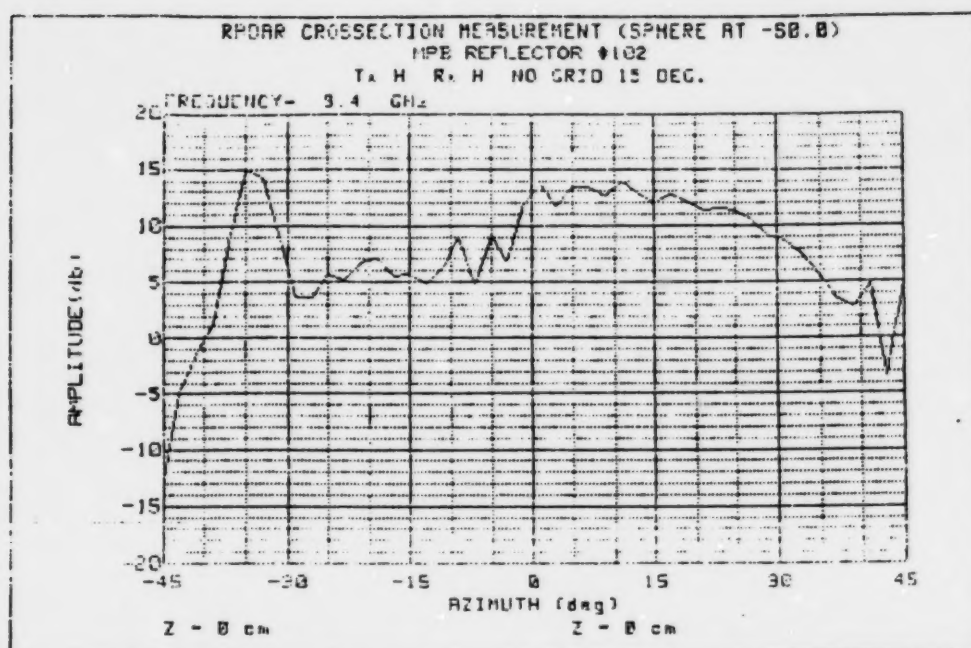
N.R.C EXP. 554 SCRN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1988 13:32:44



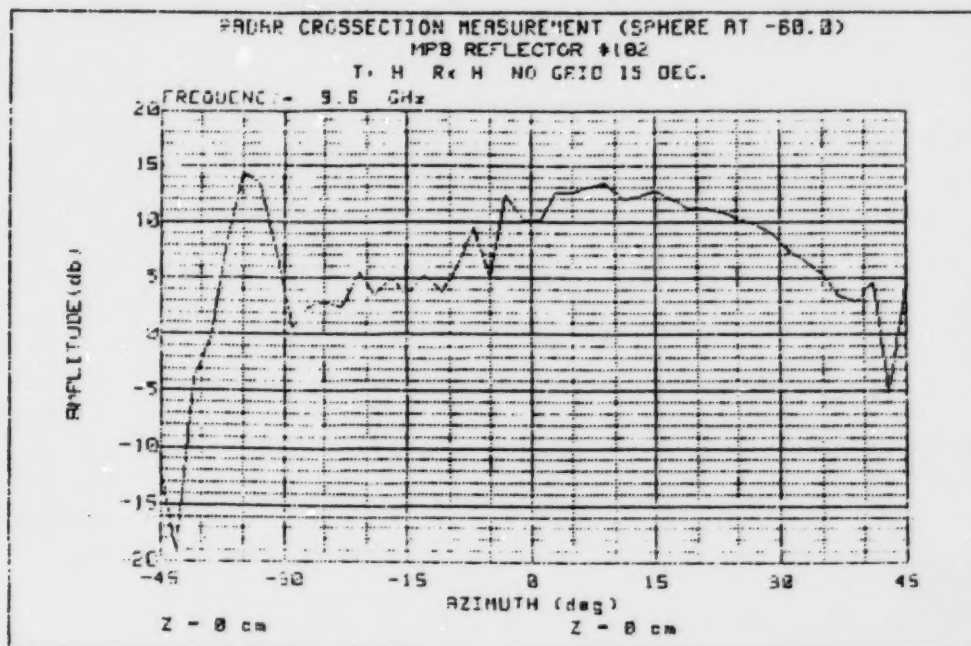
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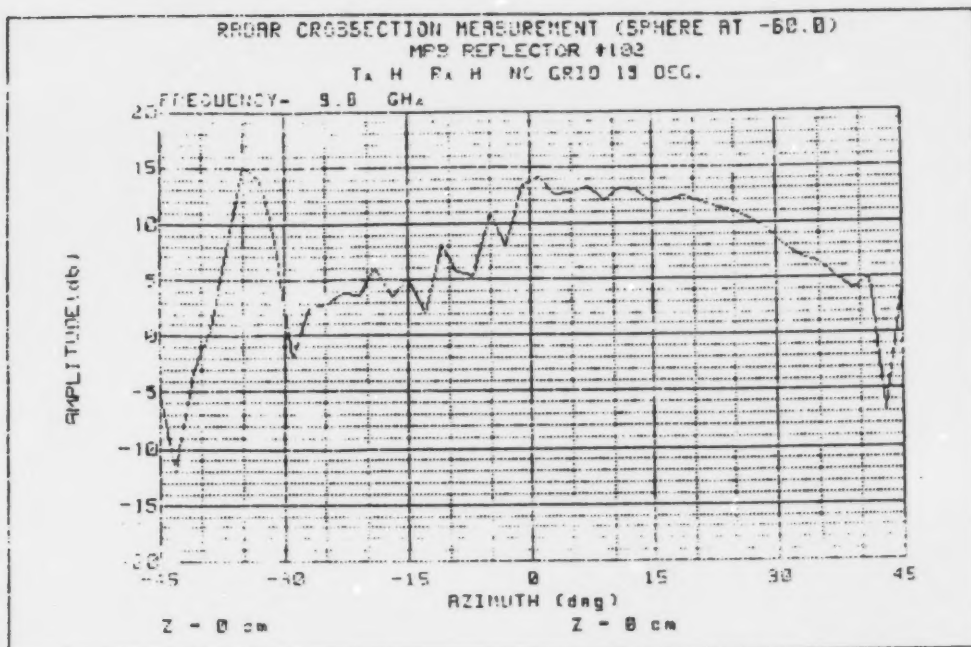
N.R.C Exp. 554 SCAN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1968 13:32:44



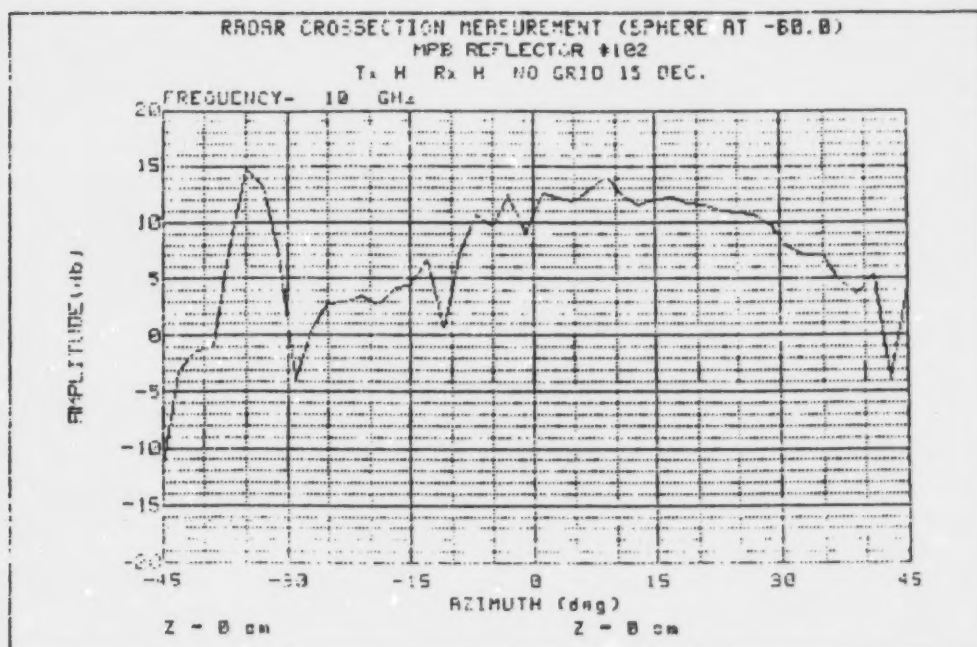
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N.R.C Exp. 554 SCW 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1963 13:52:44



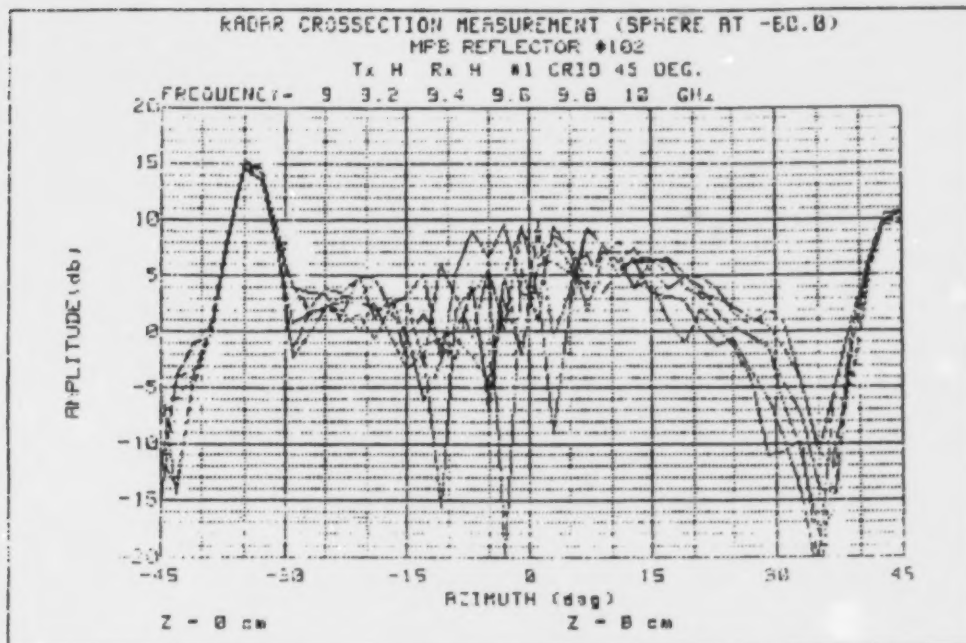
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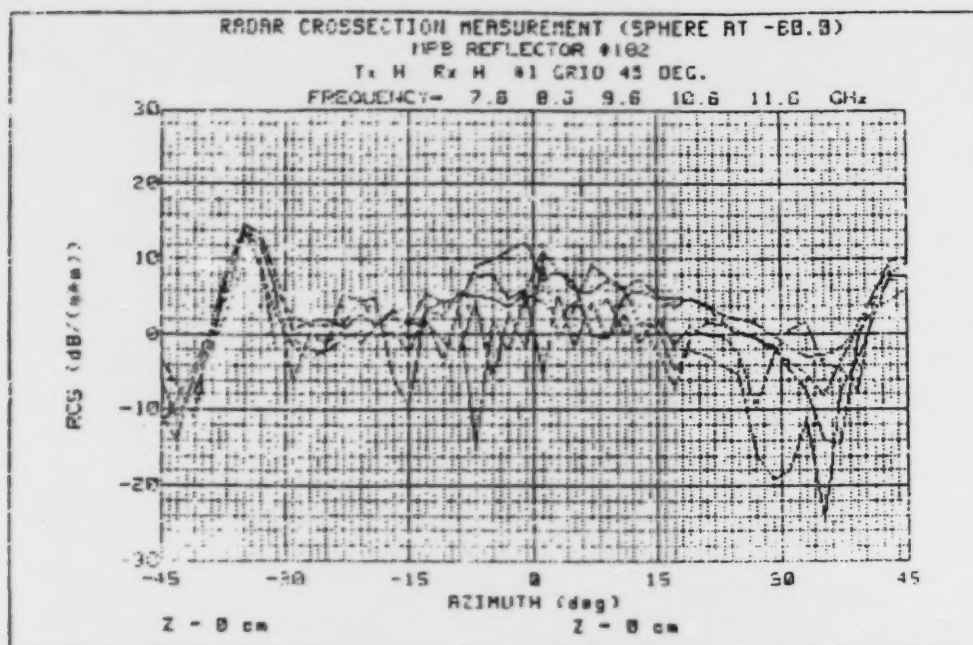
N.R.C Exp.554 SCAN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1968 13:32:44

INDOOR ANECHOIC CHAMBER

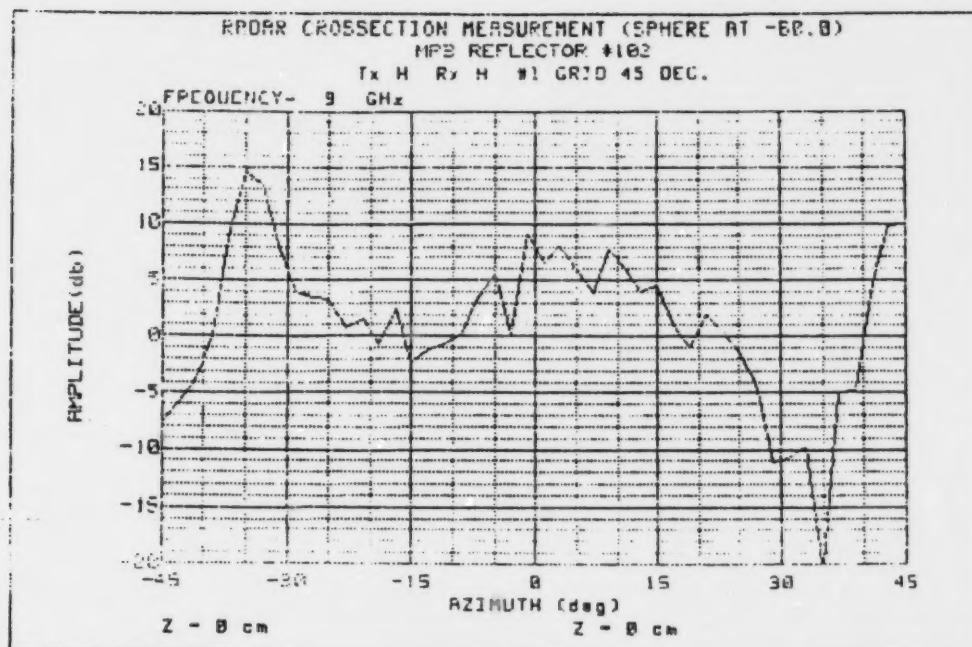
LIKE #1 GRID



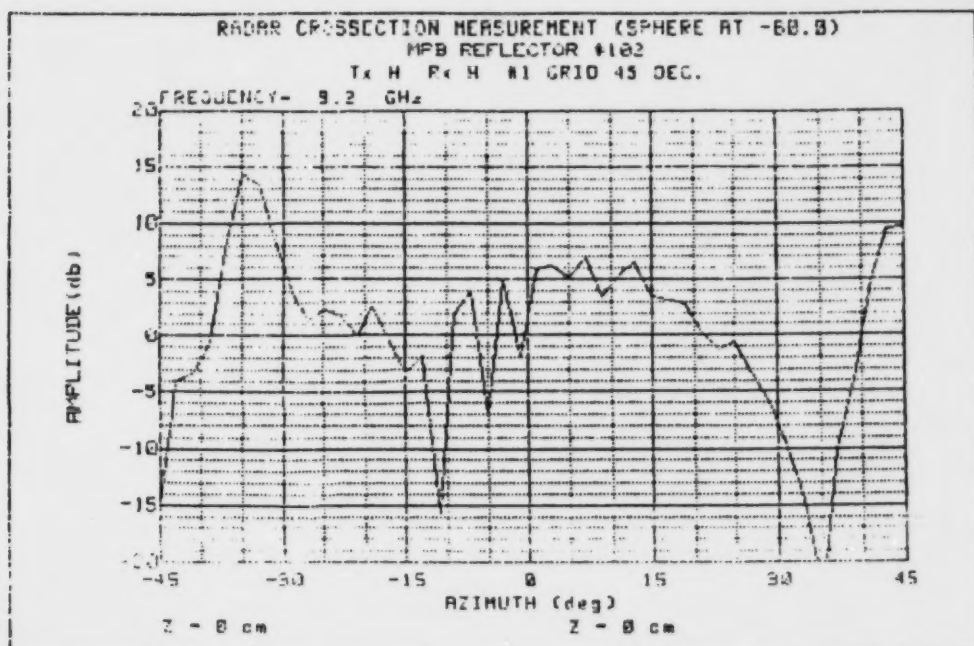
N.R.C Exp. 505 BORN 1 MEASURED BY NAME OF THE OPERATOR ON 23 Feb 1968 14:56:27



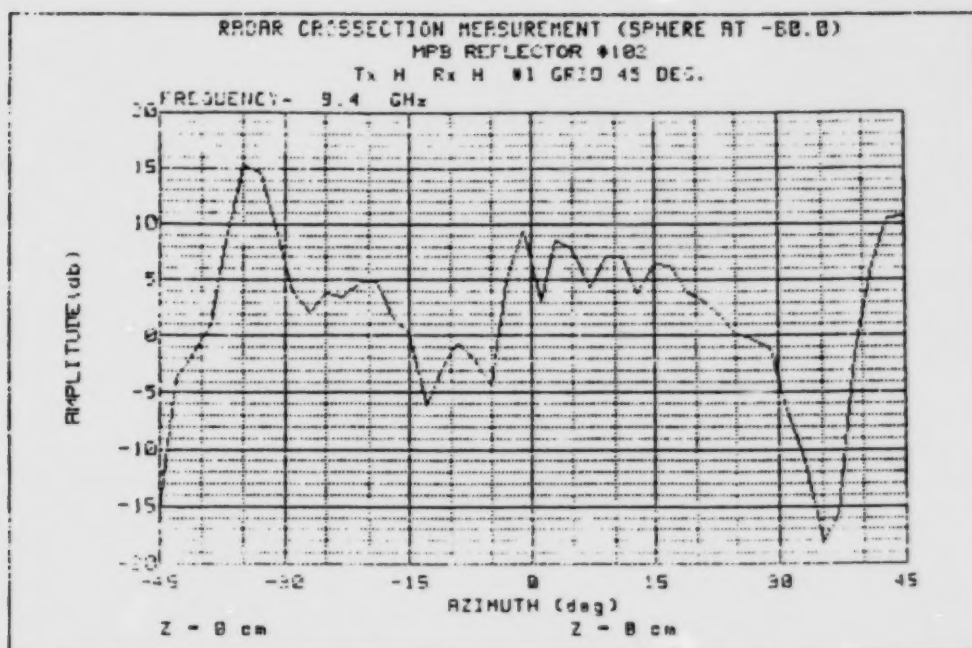
N.R.C Exp.555 SOWH 1 MEASURED BY:NAME OF THE OPERATOR ON 23 Feb 1983 14:03:27



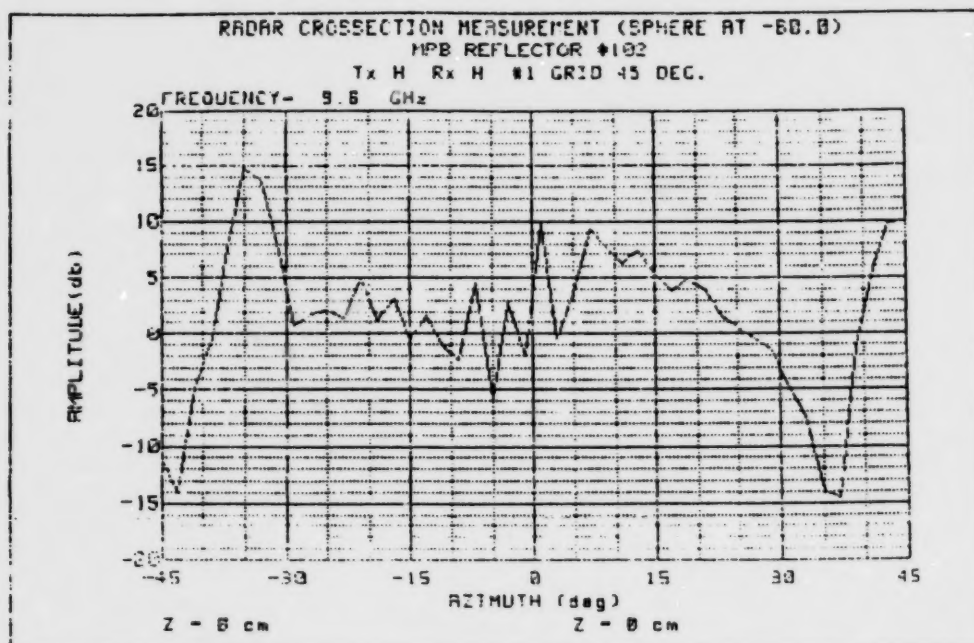
N.R.C Exp.555 SCAN 1 MEASURED BY:NAME OF THE OPERATOR ON 23 Feb 1966 14:08:27



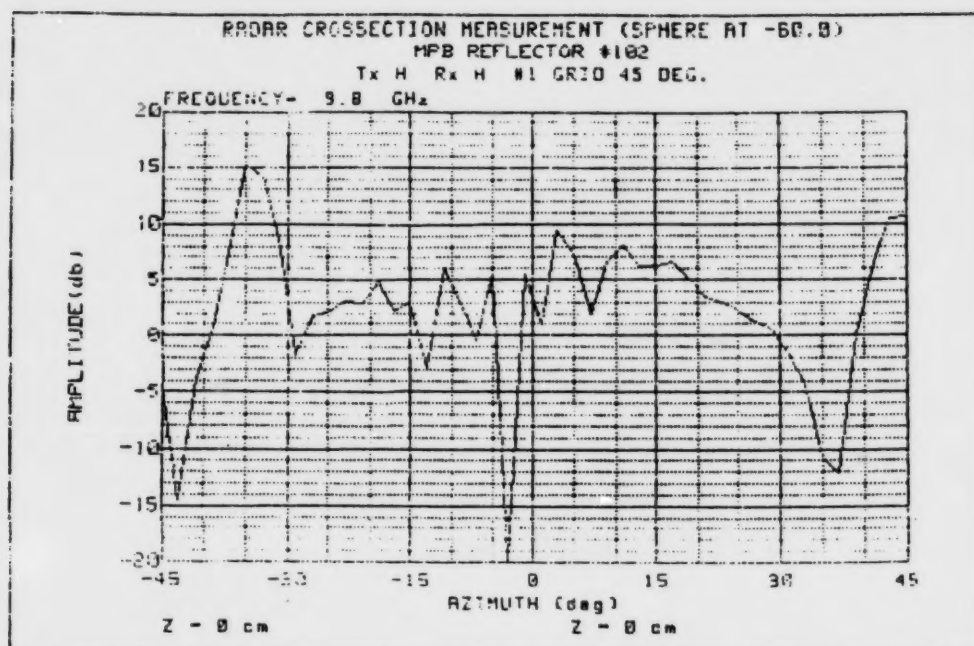
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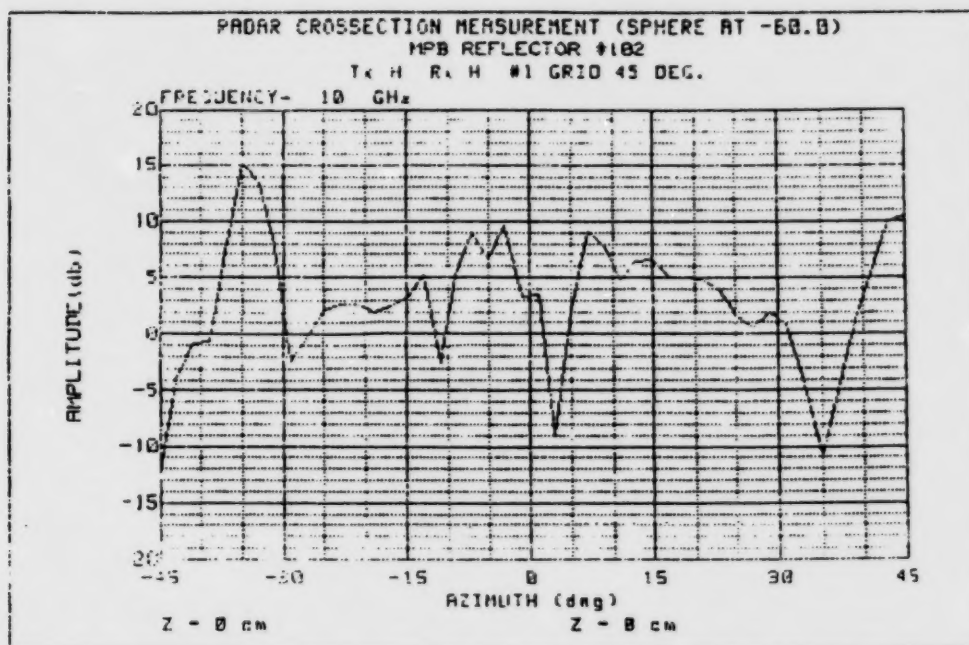
N.R.C Exp. 555 SOHN 1 MEASURED BY: NAME OF THE OPERATOR ON 29 Feb 1962 14:08:27



N.R.C Exp.555 SCAN 1 MEASURED BY:NAME OF THE OPERATOR ON 23 Feb 1963 14:03:27

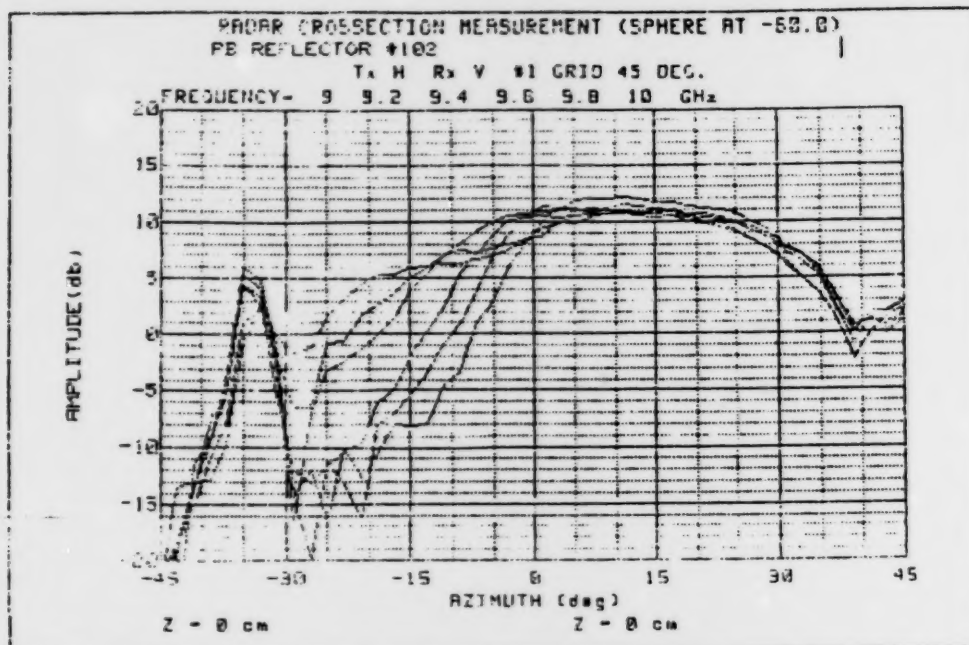


N.R.C Exp.555 SCAN 1 MEASURED BY:NAME OF THE OPERATOR ON 23 Feb 1988 14:08:27

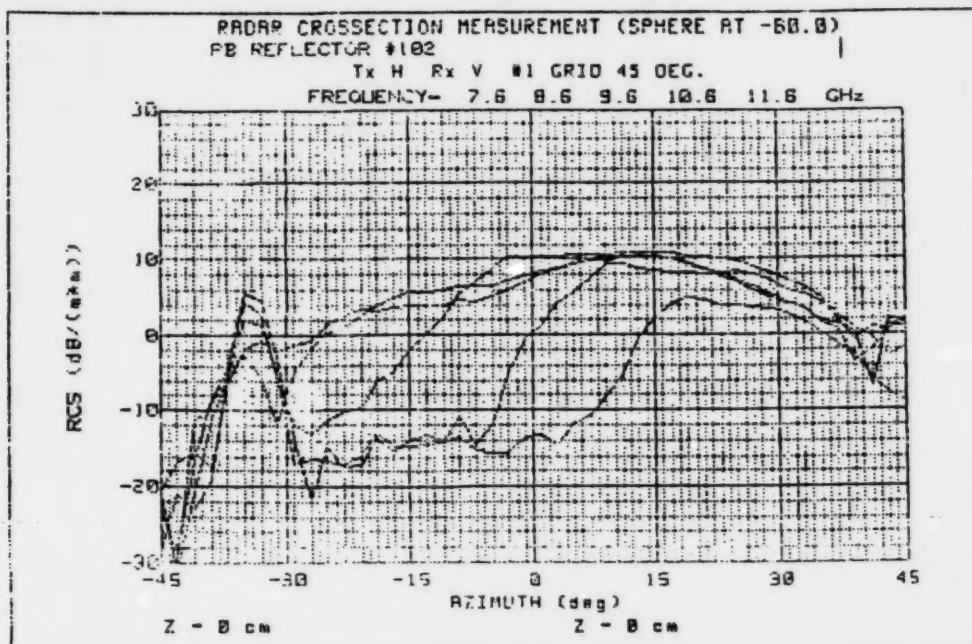


N.R.C Exp.555 SCAN 1 MEASURED BY:NAME OF THE OPERATOR ON 23 Feb 1985 14:05:27

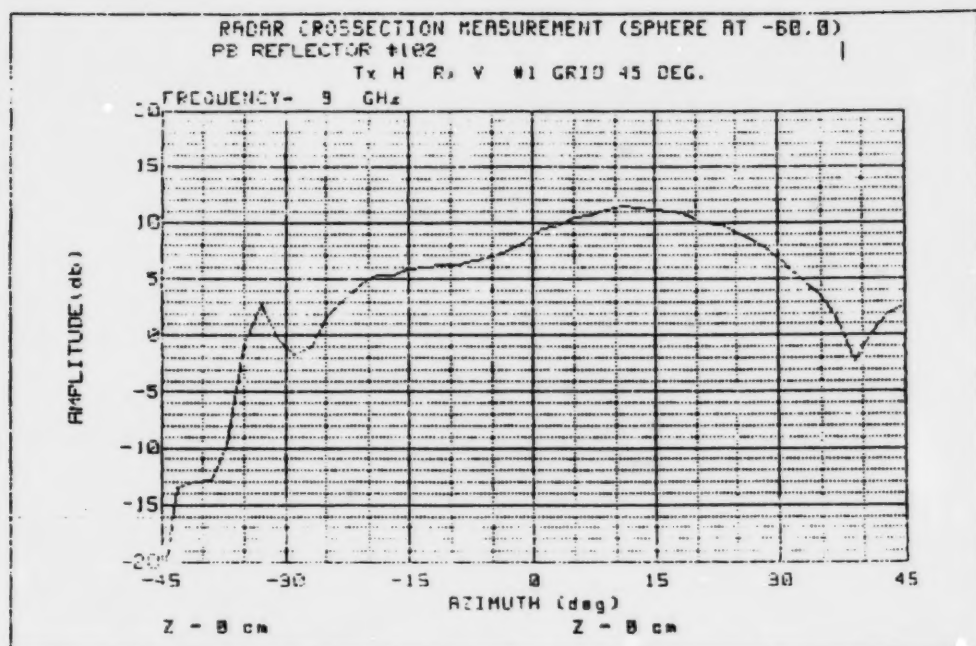
CROS #1 GRID.



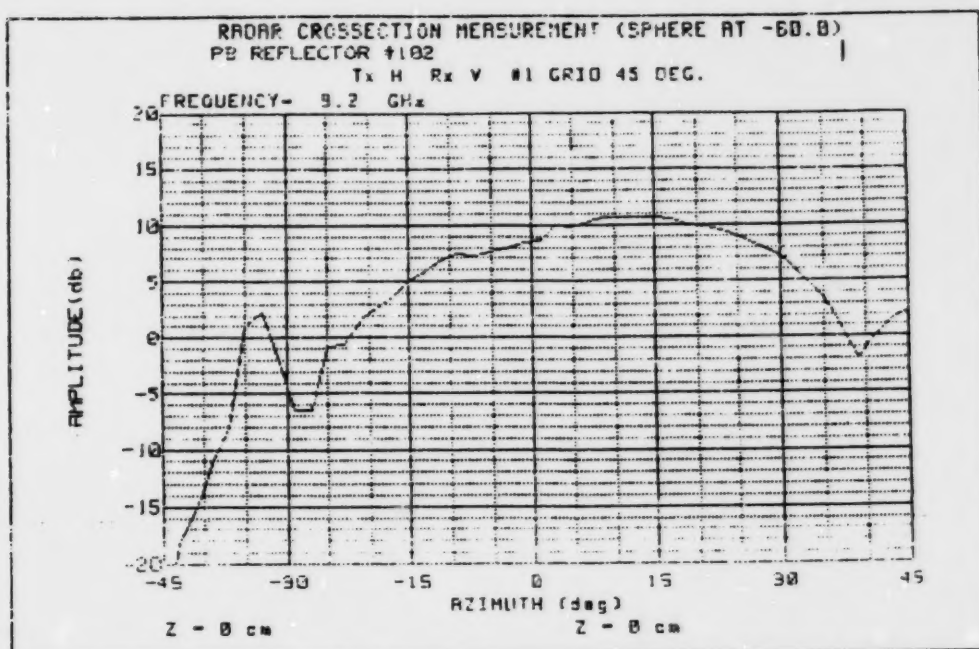
N.R.C Exp. 556 SCAN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1988 14:29:03



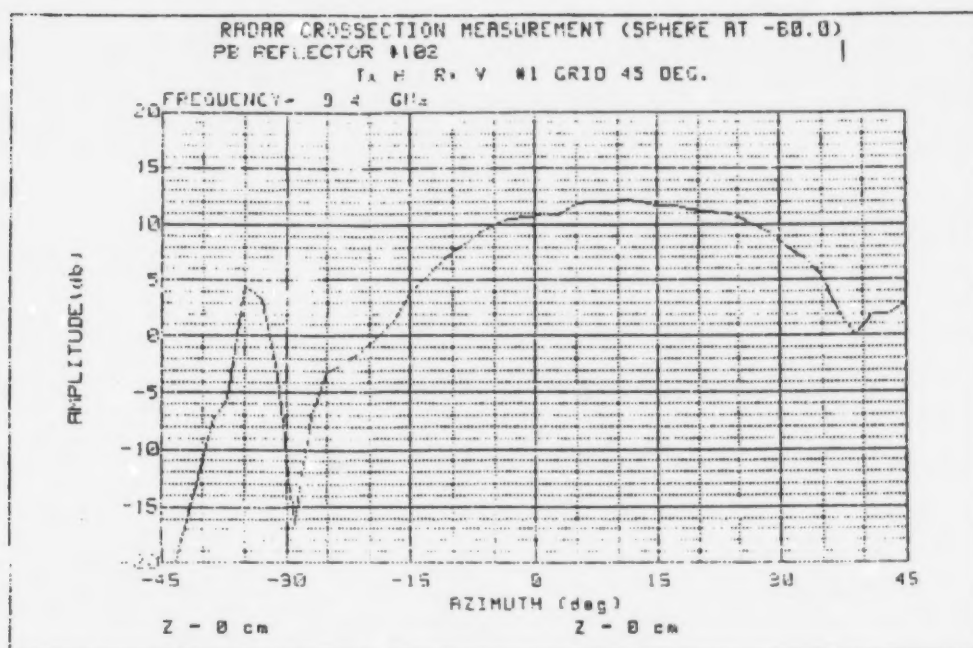
N.R.C Exp.556 SCAN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1983 14:28:03



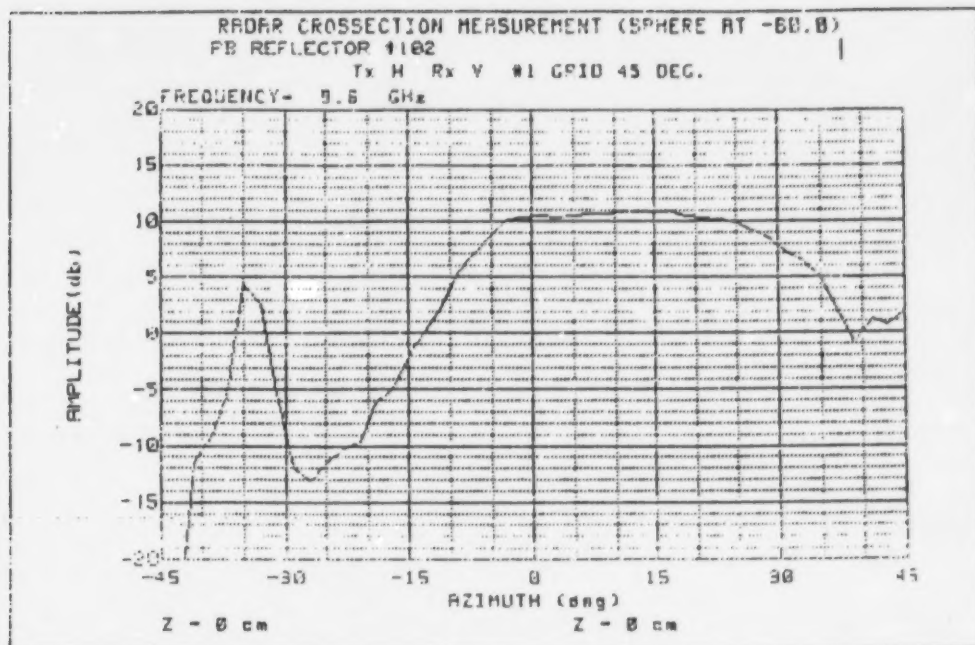
N.R.C Exp. 556 SCAN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1963 14:28:03



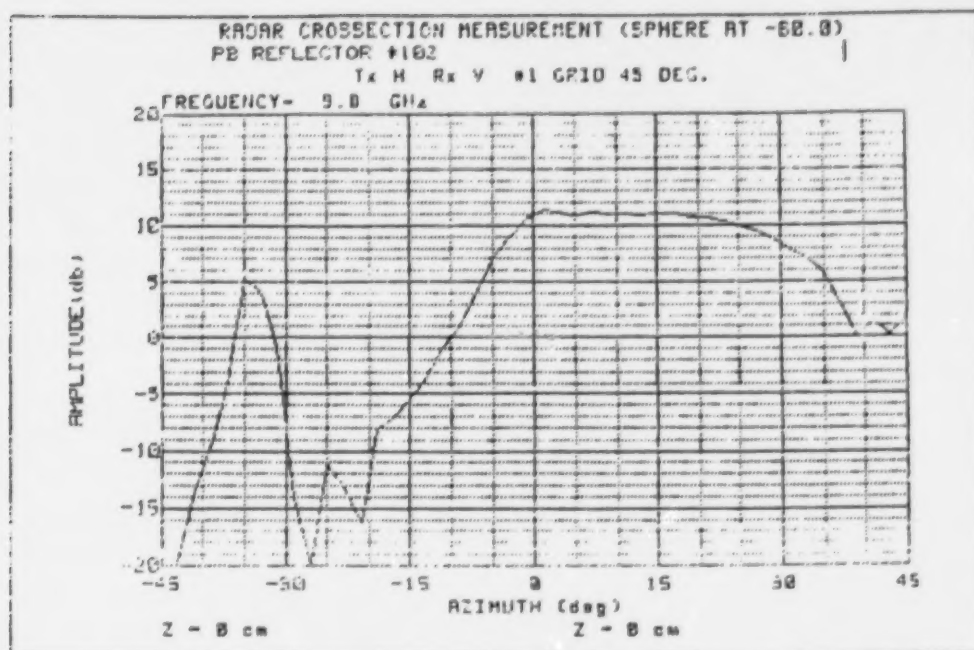
N.R.C Exp.556 SOAN 1 MEASURED BY:NAME OF THE OPERATOR ON 23 Feb 1968 14:28:03



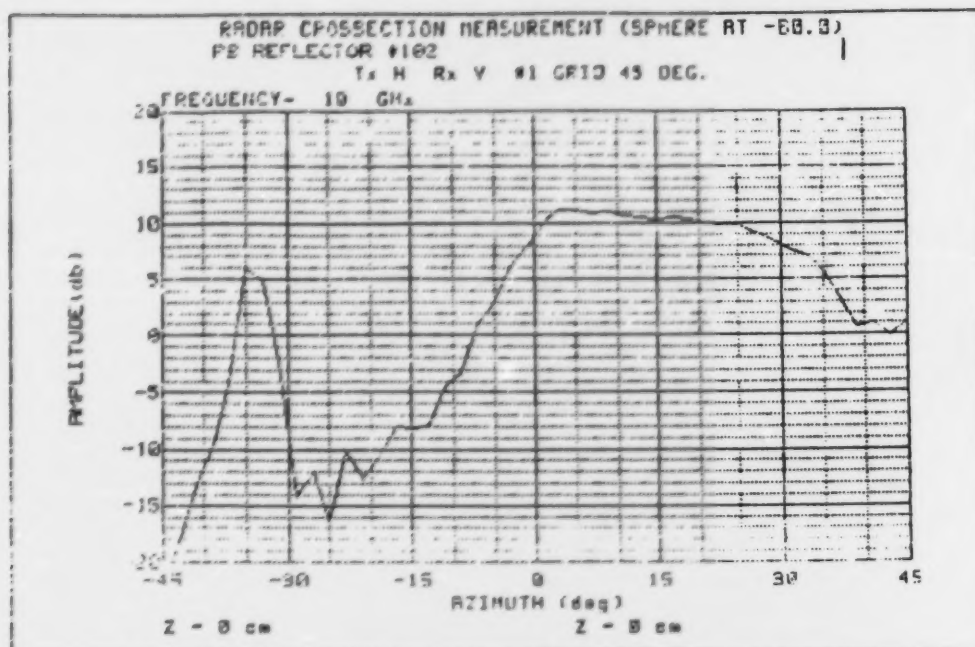
N.R.C Exp. 556 SCAN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1986 14:28:03



N.R.C Exp. 556 SQNH 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1988 14:28:03

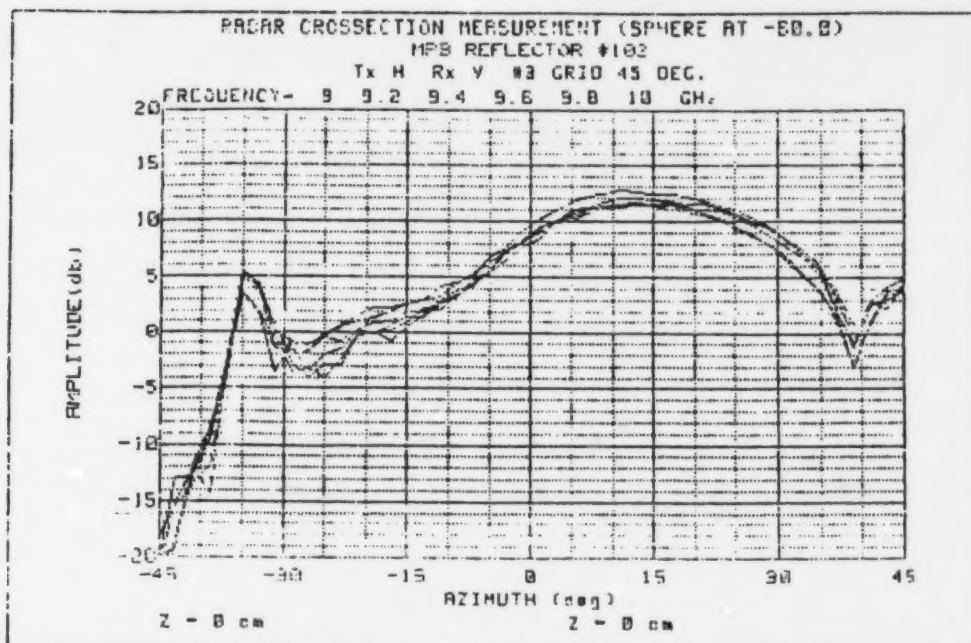


N.R.C Exp. 556 SCRN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1998 14:28:03



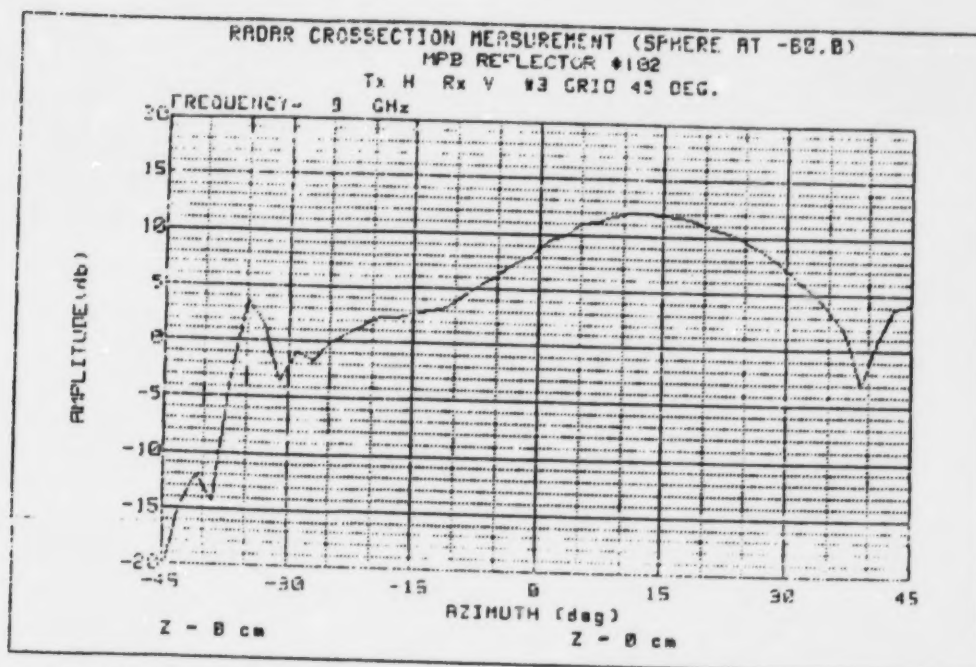
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CROSS #3 GRID

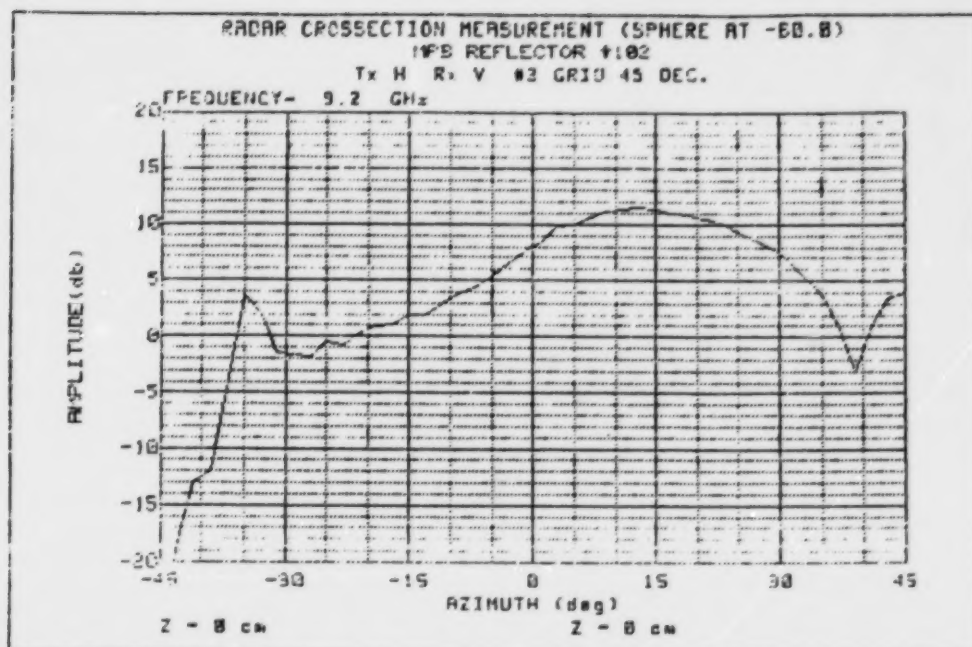


N.R.C Exp. 557 SCAN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1982 14:53:12

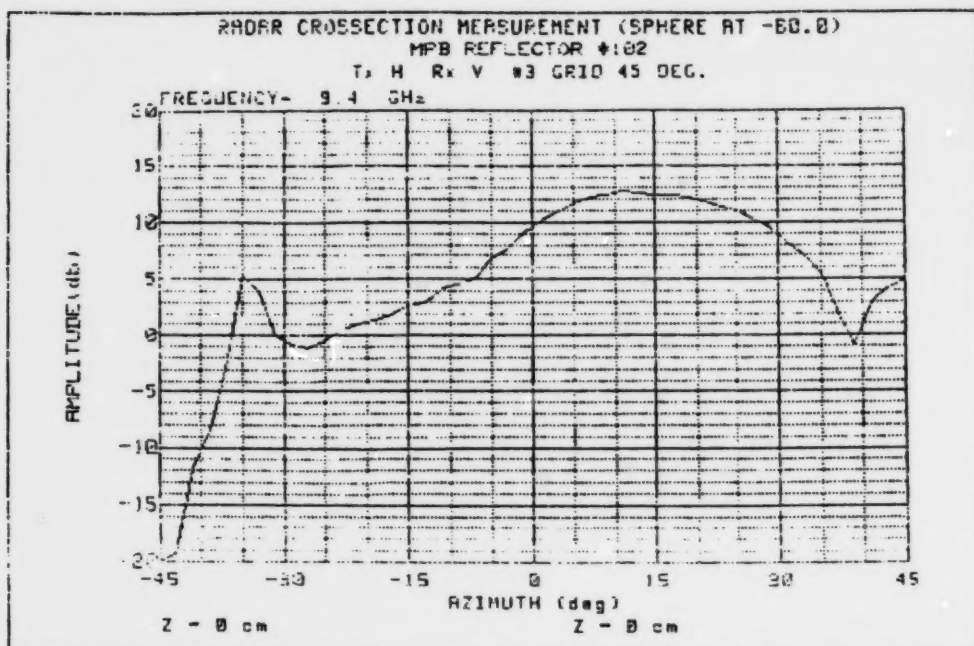
-RE-Measured for storage.



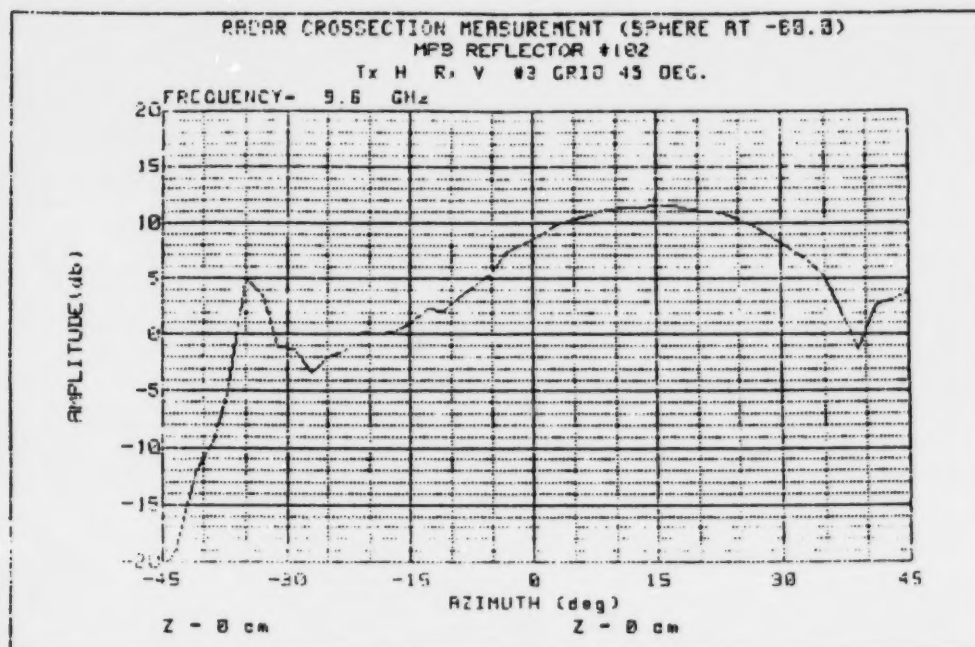
N.R.C Exp. 557 SPAN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1968 14:53:12



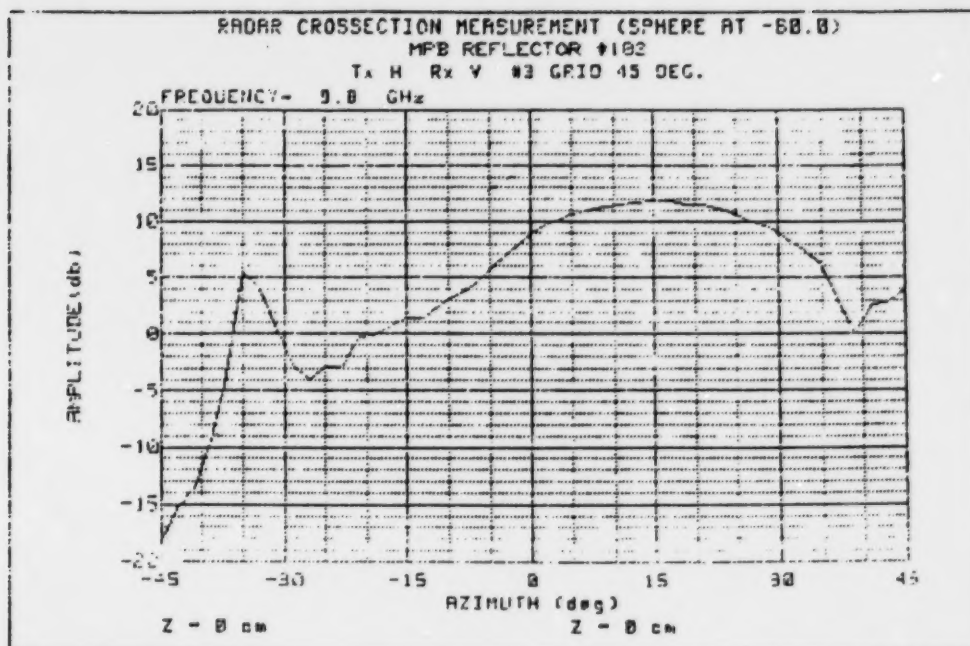
N.R.C Exp. 557 SCRN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1968 14:53:12



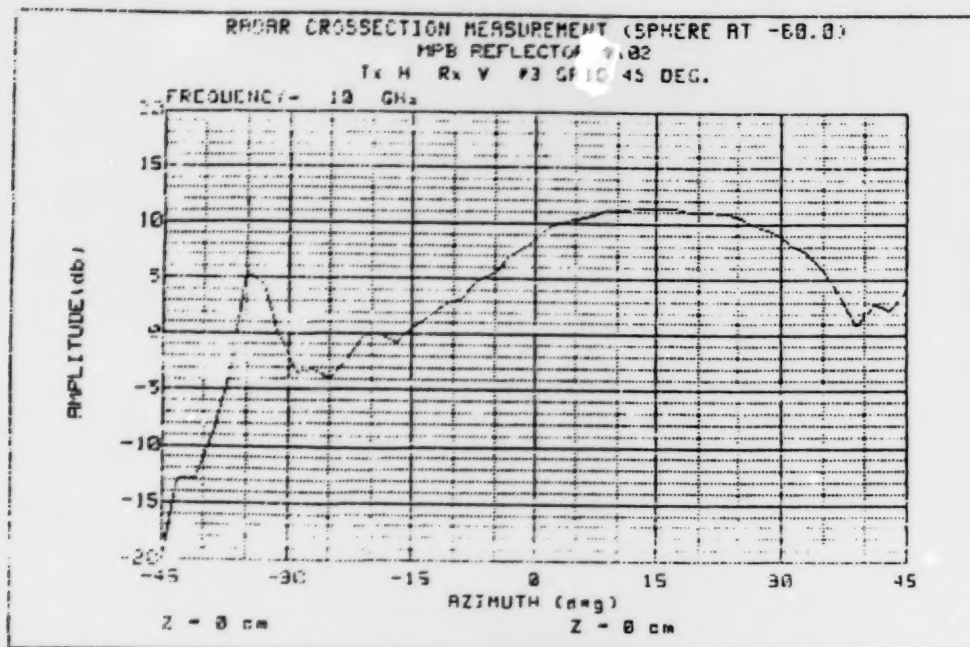
N.R.C Exp.557 SCAN 1 MEASURED BY:NAME OF THE OPERATOR ON 23 Feb 1968 14:53:12



N.R.C EAD.557 SOAN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1988 14:53:12

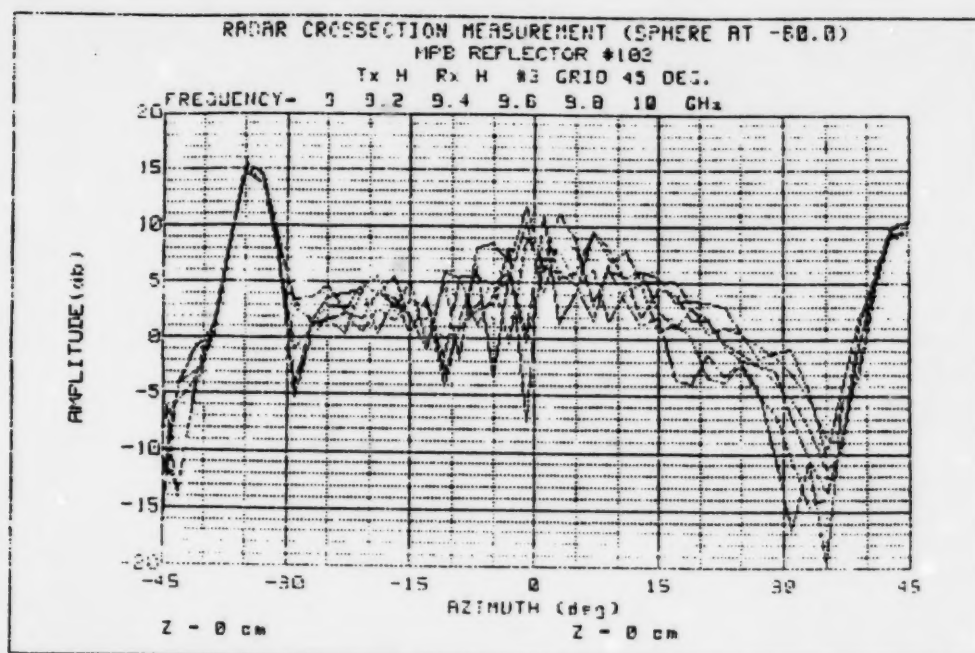


N.R.C Exp.557 SCAN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1968 14:53:12

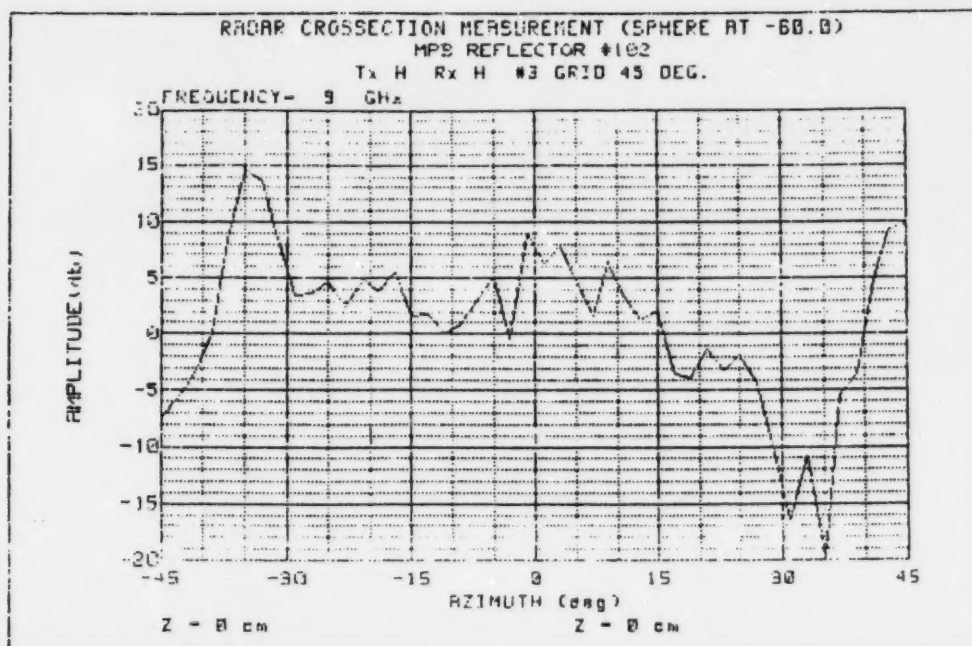


N.R.C Exp.557 BORN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1968 14:53:12

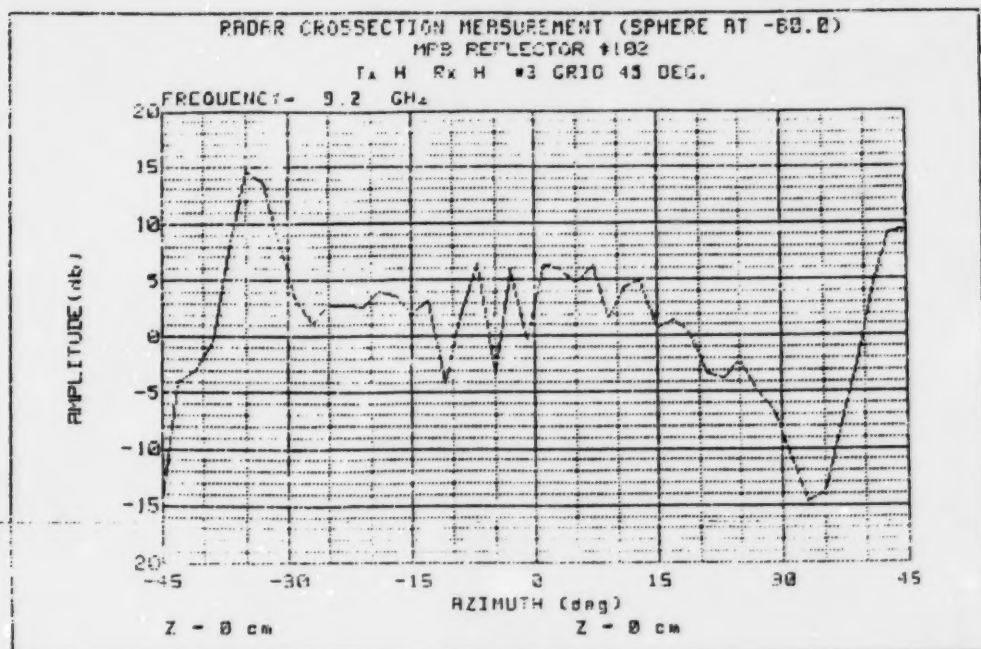
LIKE #3 GRID



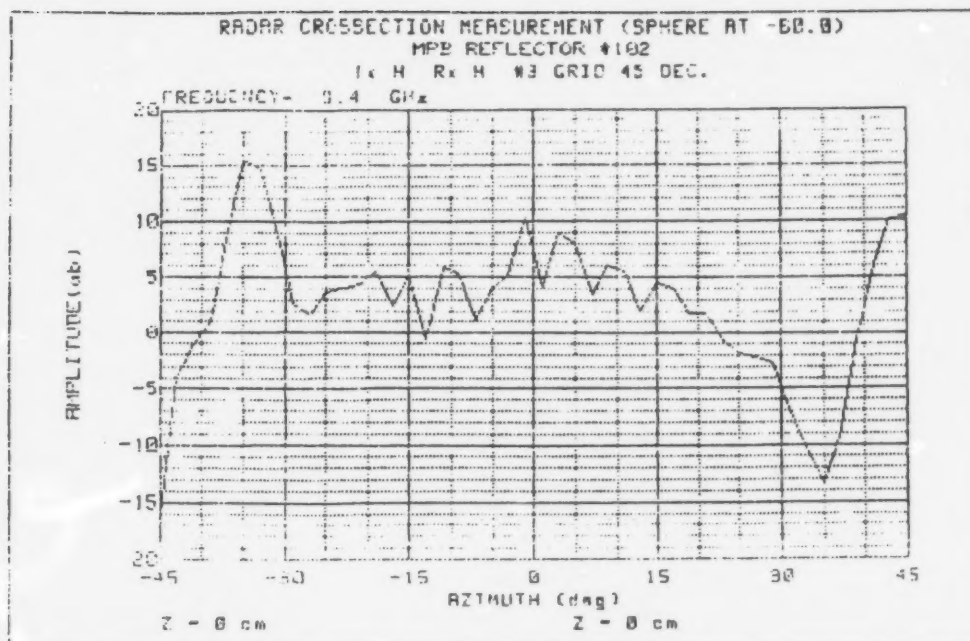
N.R.C Exp.558 SCAN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1966 15:57:18



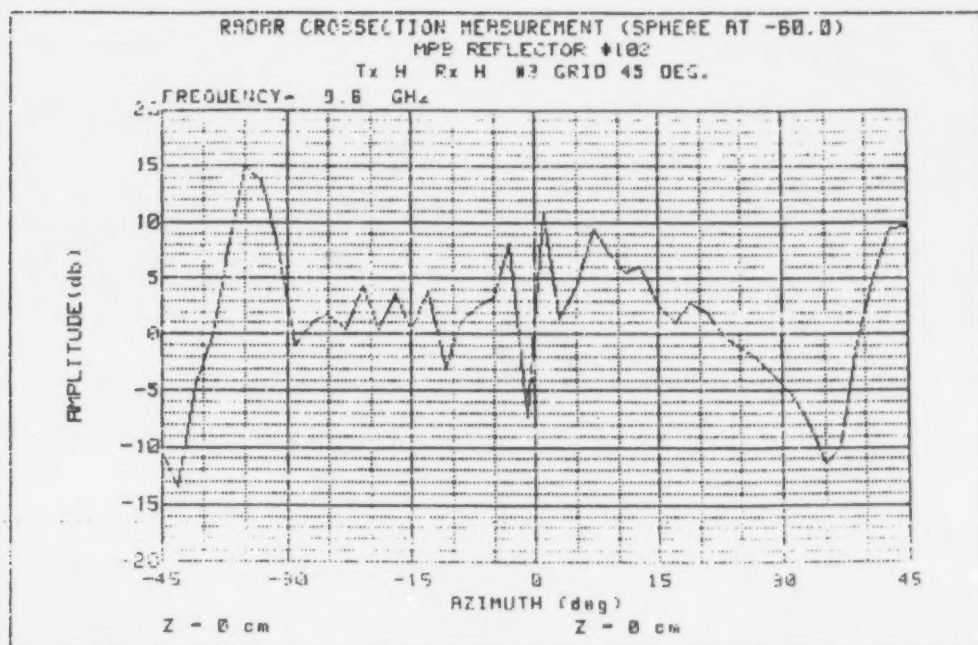
N.R.C Exp.553 SCAN 1 MEASURED BY:NAME OF THE OPERATOR ON 23 Feb 1988 15:57:18



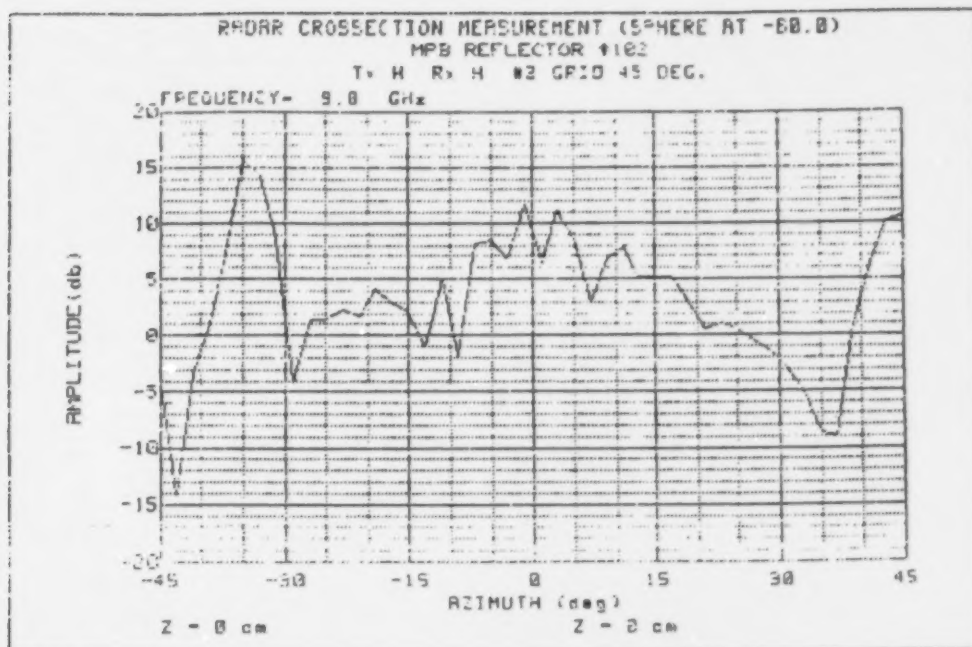
N.R.C Exp.558 SCAN 1 MEASURED BY:NAME OF THE OPERATOR ON 23 Feb 1968 15:57:18



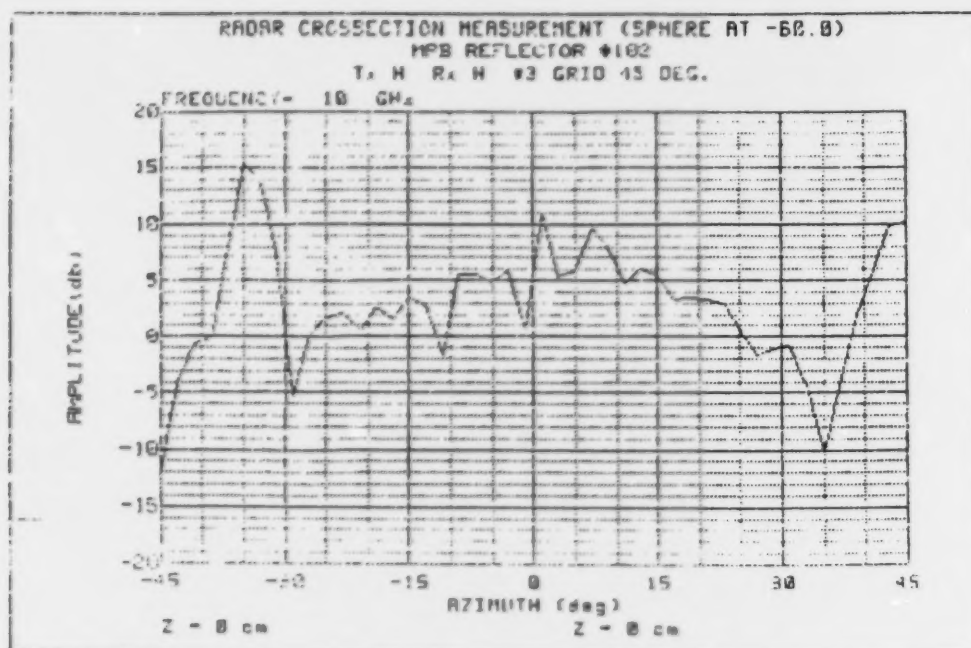
N.R.C EXP. 558 SORN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1988 15:57:18



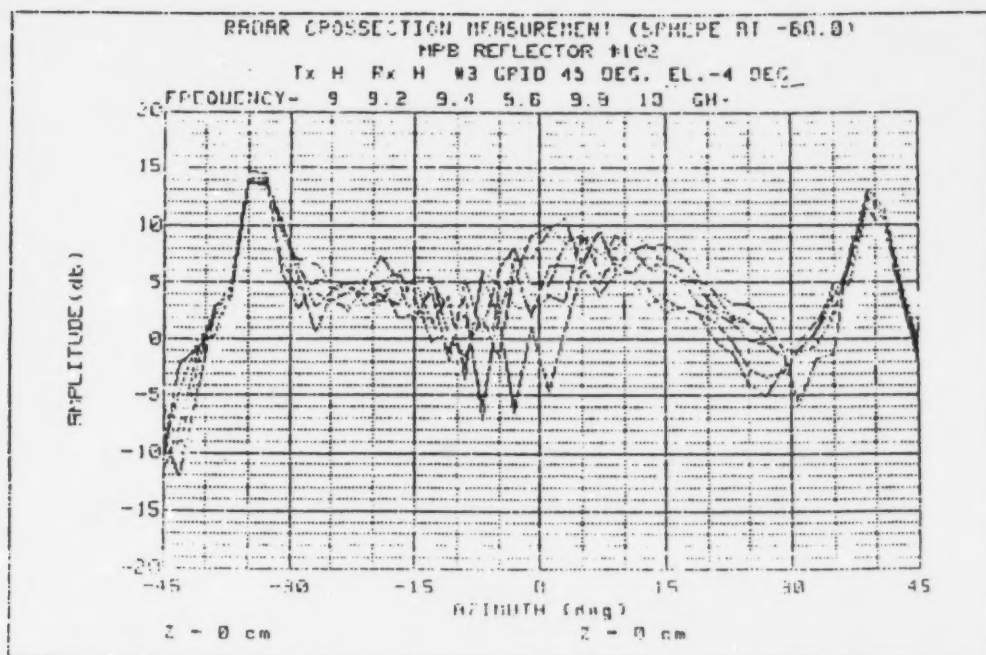
N.R.C Exp.558 SCAN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1982 15:57:18



N.R.C Exp. 558 SCRN 1 MEASURED BY: NAME OF THE OPERATOR ON 23 Feb 1966 15:57:18

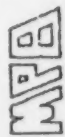


N.R.C Exp. 558 SOAR 1 MEASURED BY NAME OF THE OPERATOR ON 23 Feb 1968 15:57:18



N.R.C. Exp. 553 SCAN 1 MEASURED BY NAME OF THE OPERATOR ON 23 Feb 1963 16:30:37

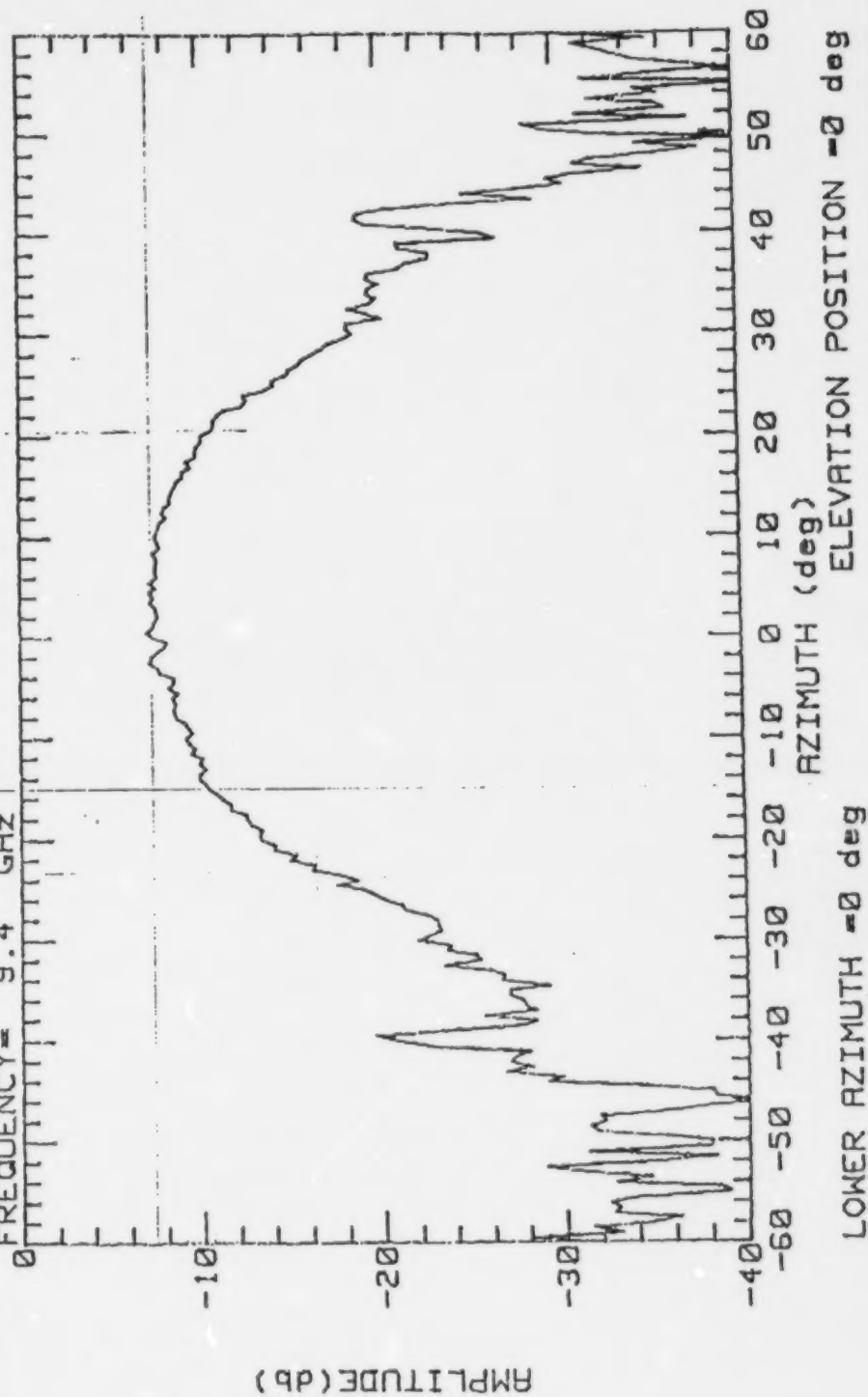
- Compare path #558
 Measured again (like path #558) with reflector tilted down $\approx 4^\circ$
 in attempt to determine if large variations are due to
 interaction of signals reflected from beveled and flat
 front face edges + plywood support structure.



MPB TECHNOLOGIES INC. CORNER REFLECTOR MPB #100 JUNE 27, 1988

TX.H RX.V GRID 45.() Deg.ABSORBER BETWEEN HORNS

FREQUENCY= 9.4 GHz



LOWER AZIMUTH = 0 deg

AZIMUTH (deg)

ELEVATION POSITION = 0 deg

MPB TECHNOLOGIES INC. Exp.165SCAN 1 BY:L. ALLAN

ON 27 Mar 1988 14:12:12

MPA

TECHNOLOGIES INC.

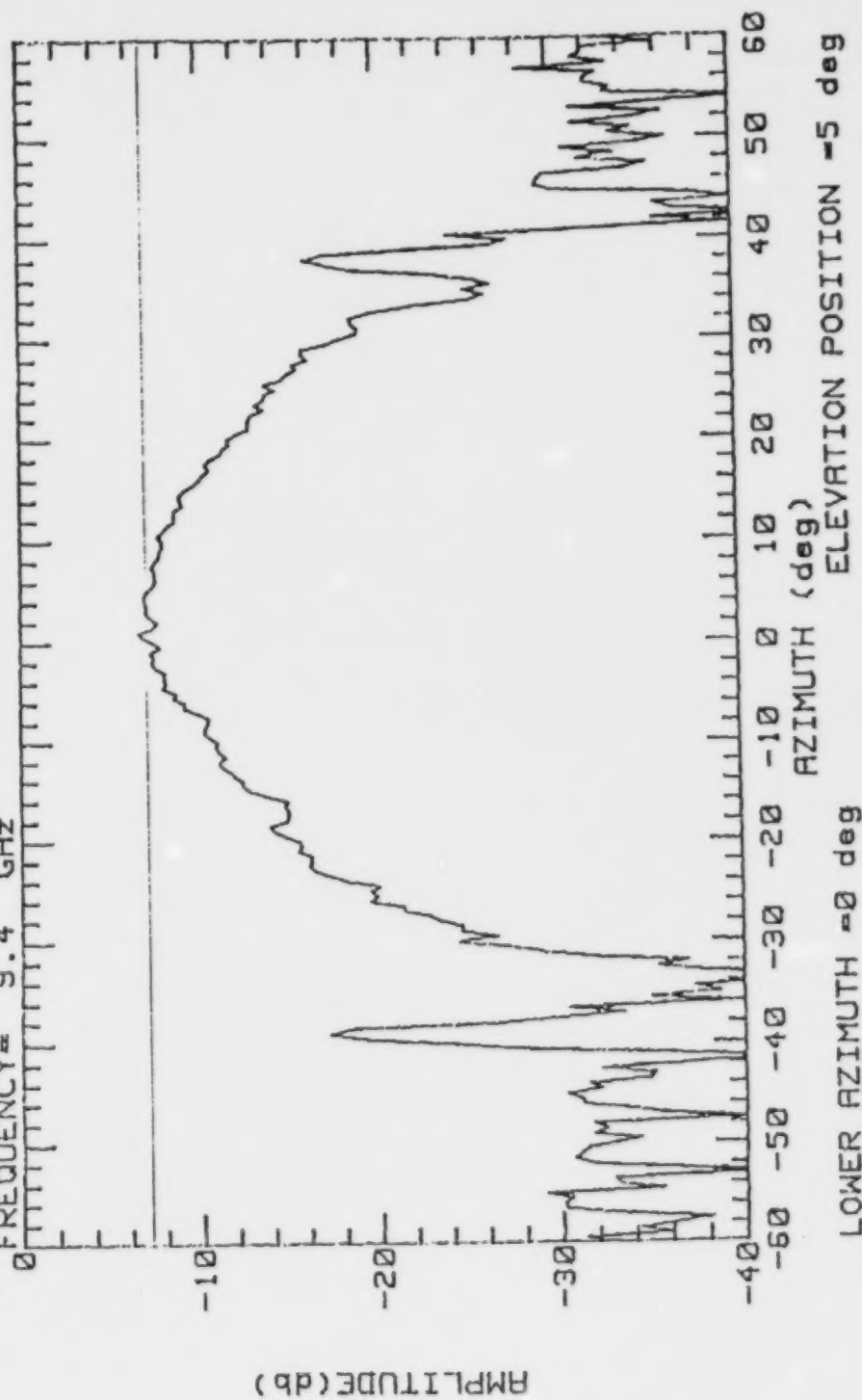
MPB TECHNOLOGIES INC.

CORNER REFLECTOR MPB #100

Tx.H Rx.V GRID 45.() Deg.ABSORBER BETWEEN HORNS

JUNE 27, 1988

FREQUENCY = 9.4 GHz



MPB TECHNOLOGIES INC. Exp.166SCAN 1 BY:L. ALLAN

ON 27 Mar 1988 14:15:17

MPB

TECHNOLOGIES INC.

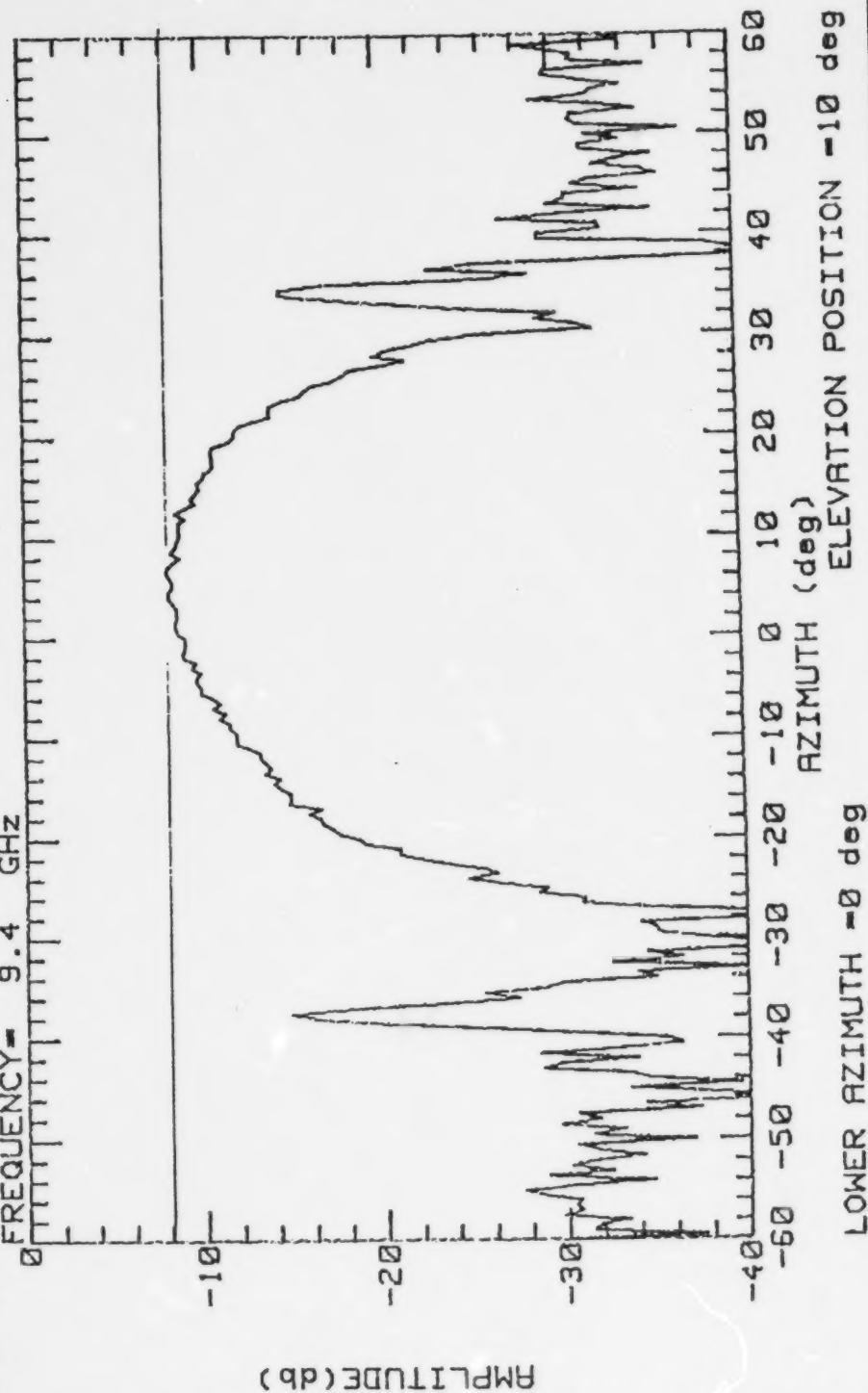
MPB TECHNOLOGIES INC.

CORNER REFLECTOR MPB #100

Tx.H Rx.V GRID 45.() Deg.ABSORBER BETWEEN HORNS

JUNE 27, 1988

FREQUENCY = 9.4 GHz



MPB TECHNOLOGIES INC. Exp.167SCAN 1 BY:L. ALLAN

ON 27 Mar 1988 14:18:23

MPB

TECHNOLOGIES INC.

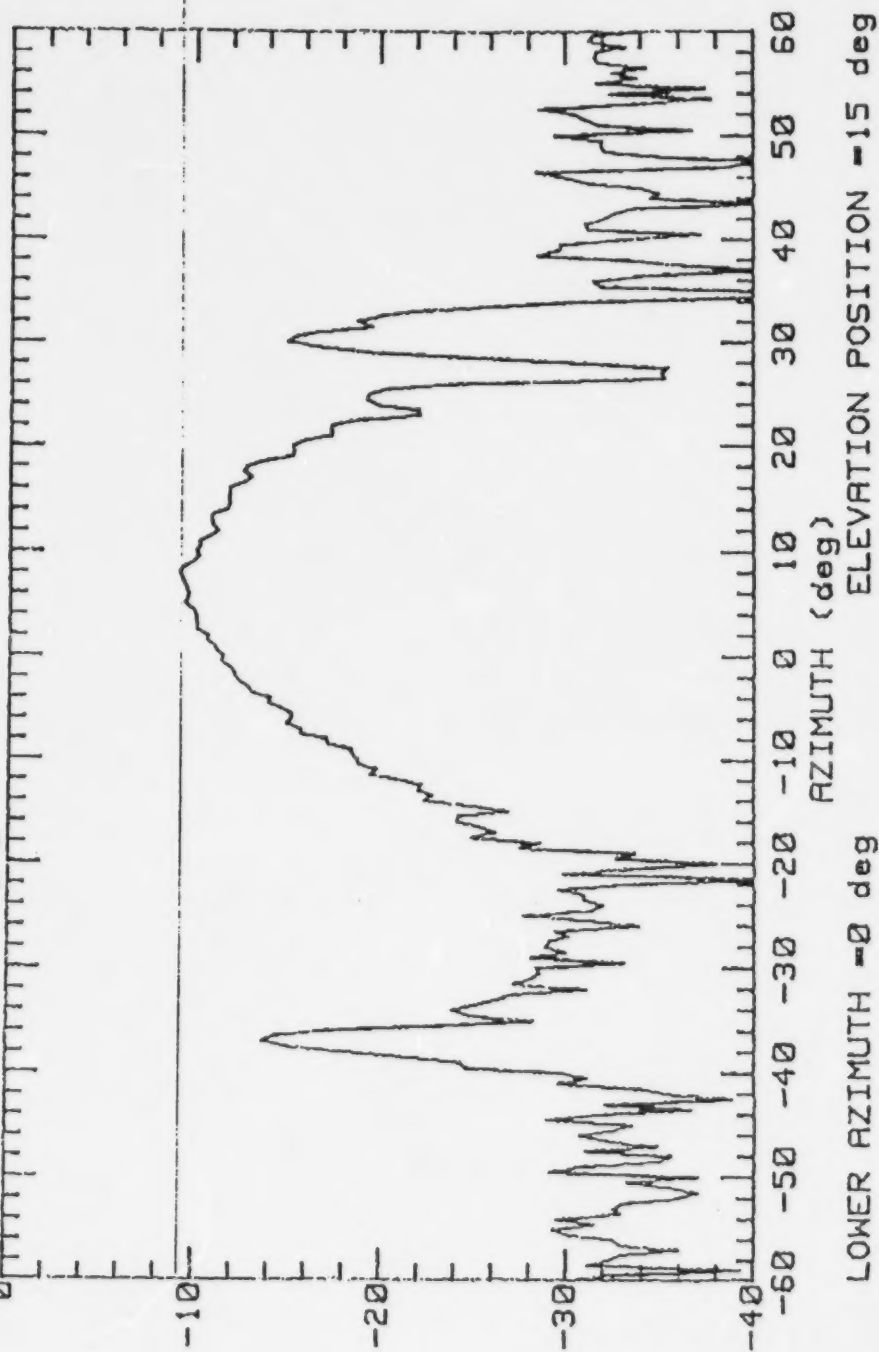
MPB TECHNOLOGIES INC.

CORNER REFLECTOR MPB #100

JUNE 27, 1988

Tx.H Rx.V GRID 45.() Deg.ABSORBER BETWEEN HORNS

FREQUENCY = 9.4 GHz



MPB TECHNOLOGIES INC. Exp.168SCAN 1 BY:L. ALLAN

ON 27 Mar 1988 14:21:08

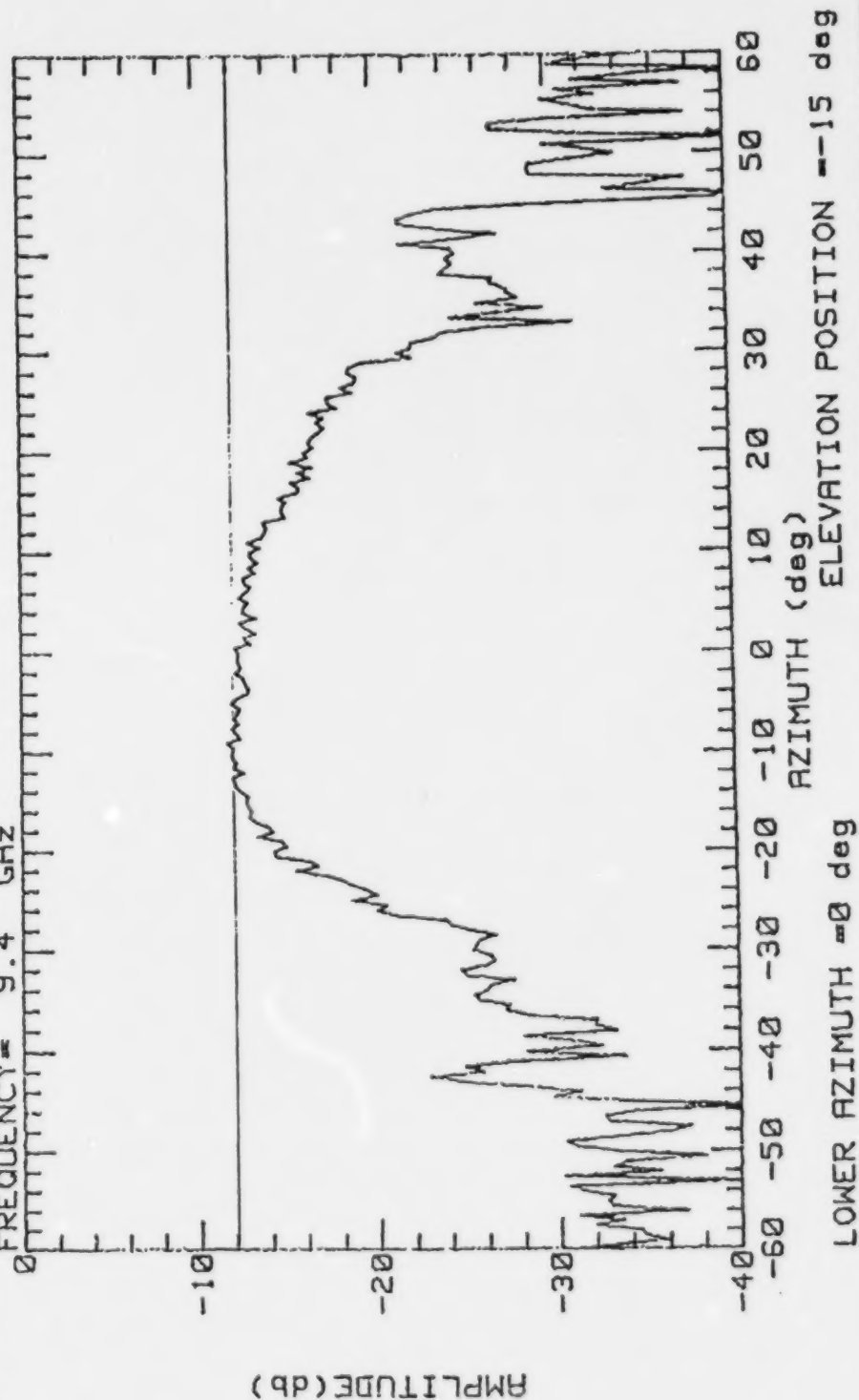
MPB
TECHNOLOGIES INC.

MPB TECHNOLOGIES INC.

CORNER REFLECTOR MPB #100
Tx.H Rx.V GRID 45.() Deg.ABSORBER BETWEEN HORNS

JUNE 27, 1988

FREQUENCY = 9.4 GHz



MPB TECHNOLOGIES INC. Exp. 169SCAN 1 BY:L. ALLAN

ON 27 Mar 1988 14:26:02

MPB

TECHNOLOGIES INC.

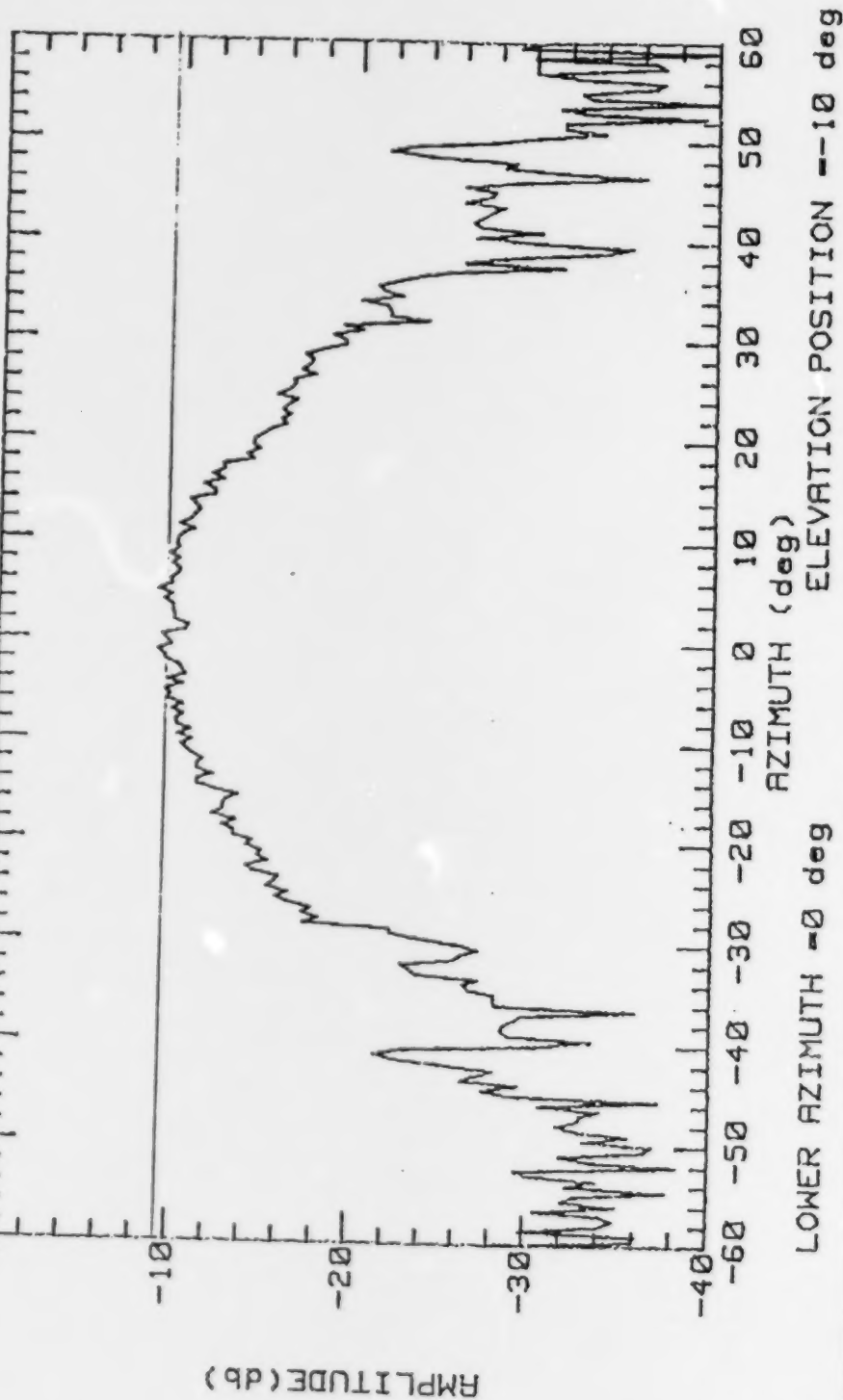
MPB TECHNOLOGIES INC.

CORNER REFLECTOR MPB #100

JUNE 27, 1988

Tx.H Rx.V GRID 45.() Deg.ABSORBER BETWEEN HORNS

FREQUENCY = 9.4 GHz



MPB TECHNOLOGIES INC. Exp.170SCAN 1 BY:L. ALLAN

ON 27 Mar 1988 14:28:48

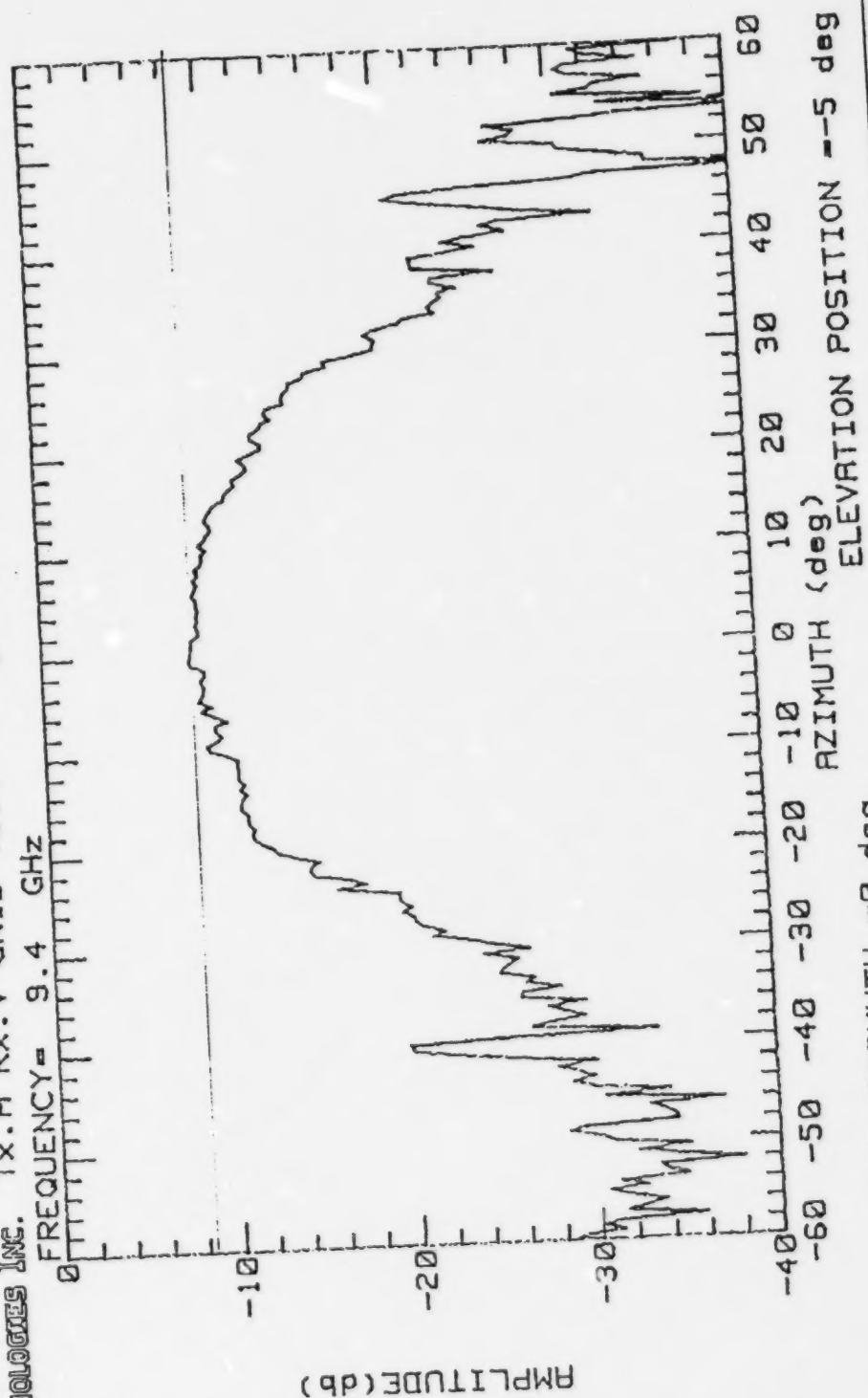
MPB

TECHNOLOGIES INC.

MPB TECHNOLOGIES INC.

JUNE 27, 1988
CORNER REFLECTOR MPB #100
Tx. H Rx. V GRID 45. () Deg. ABSORBER BETWEEN HORNS

FREQUENCY = 9.4 GHz



LOWER AZIMUTH = 0 deg

MPB TECHNOLOGIES INC. Exp. 171SCAN 1 BY: L. ALLAN

ON 27 Mar 1988 14:32:38

MPA

TECHNOLOGIES INC.

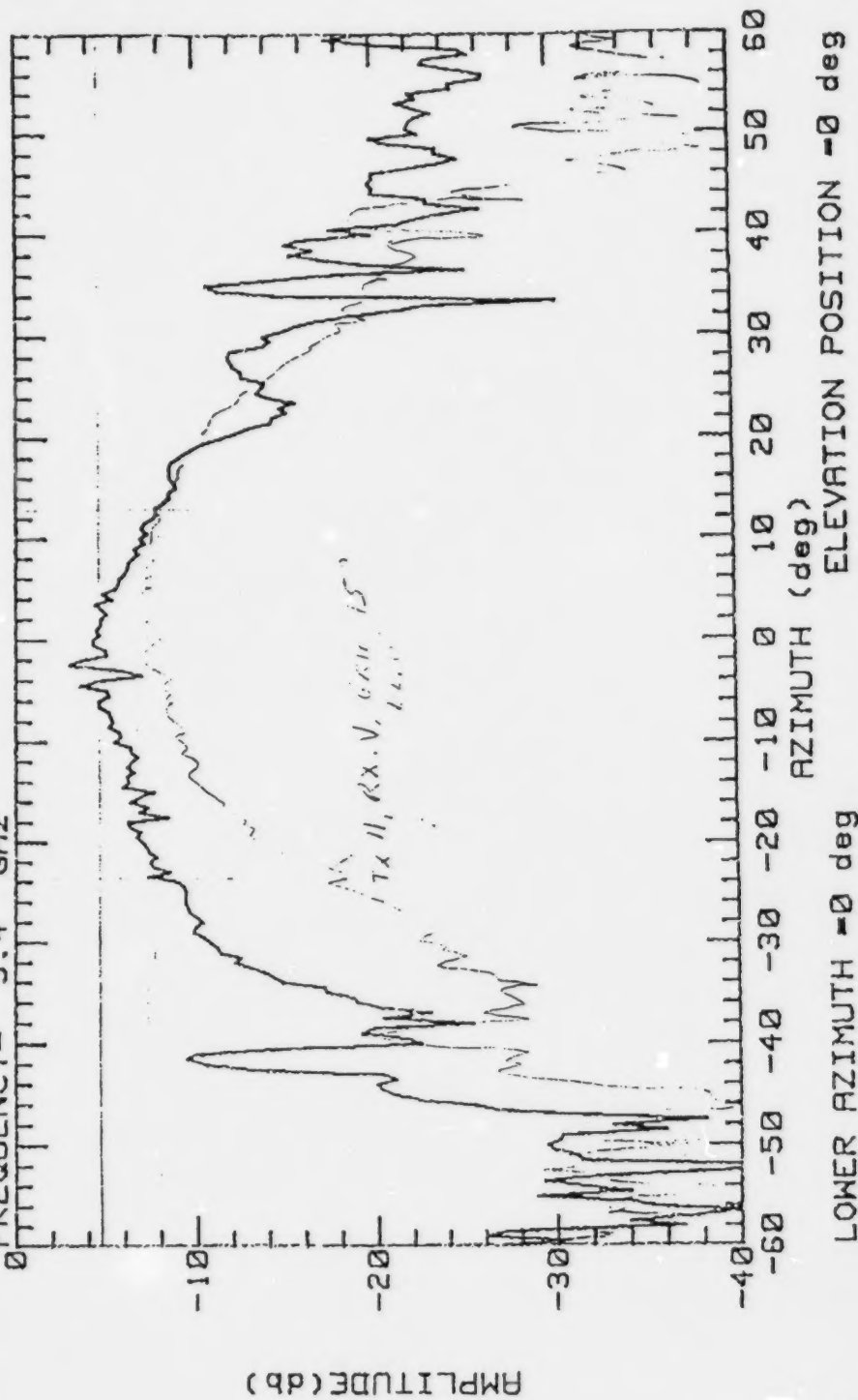
MPB TECHNOLOGIES INC.

CORNER REFLECTOR MPB #100

JUNE 27, 1988

Tx.H Rx.H GRID 90.(V) Deg.ABSORBER BETWEEN HORNS

FREQUENCY= 9.4 GHz

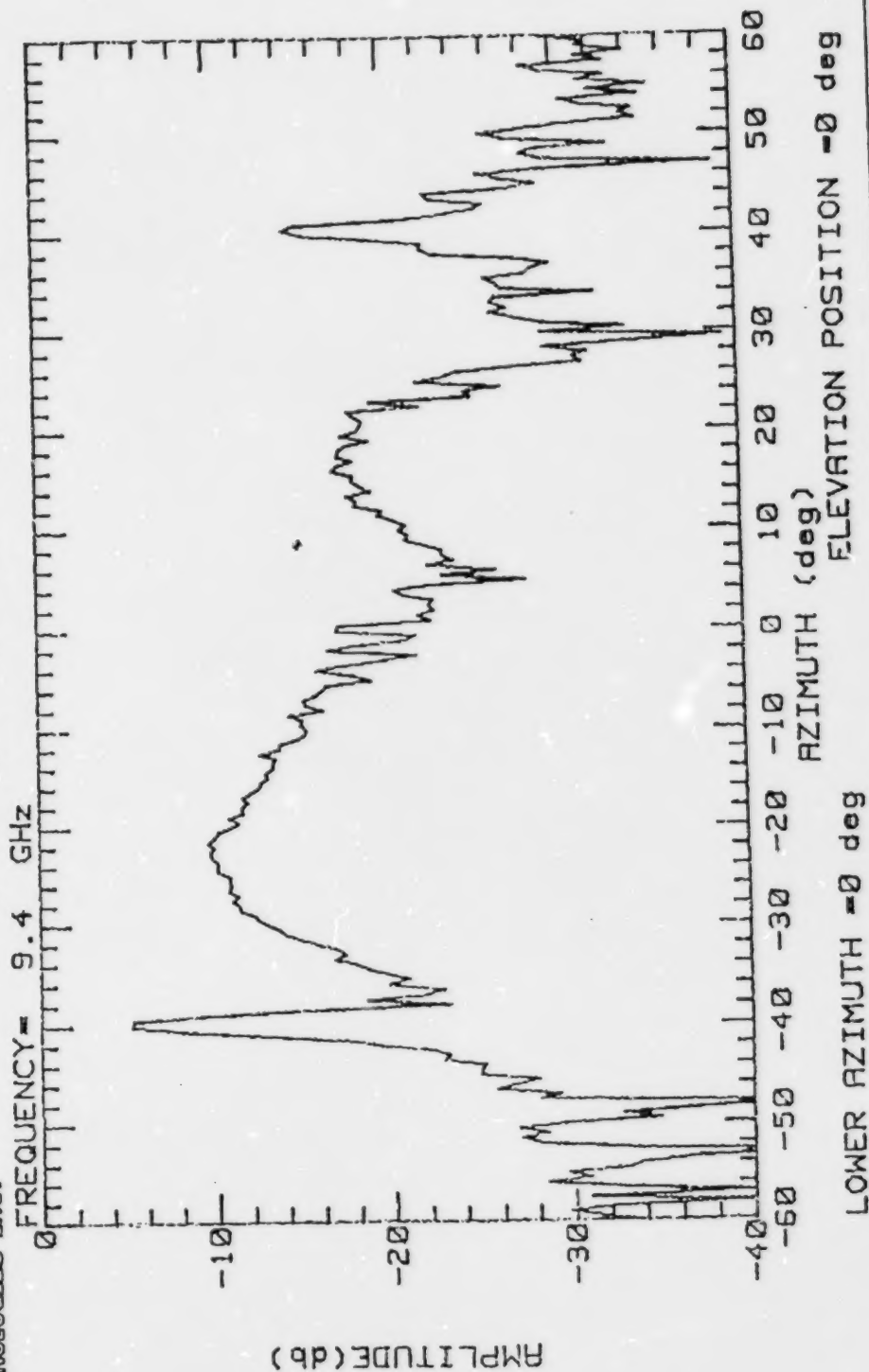


MPB TECHNOLOGIES INC. Exp.173SCAN 1 BY:L. ALLAN

ON 27 Mar 1988 15:02:14

MPB
TECHNOLOGIES INC.

MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #100
Tx.H Rx.H GRID 45.() Deg.



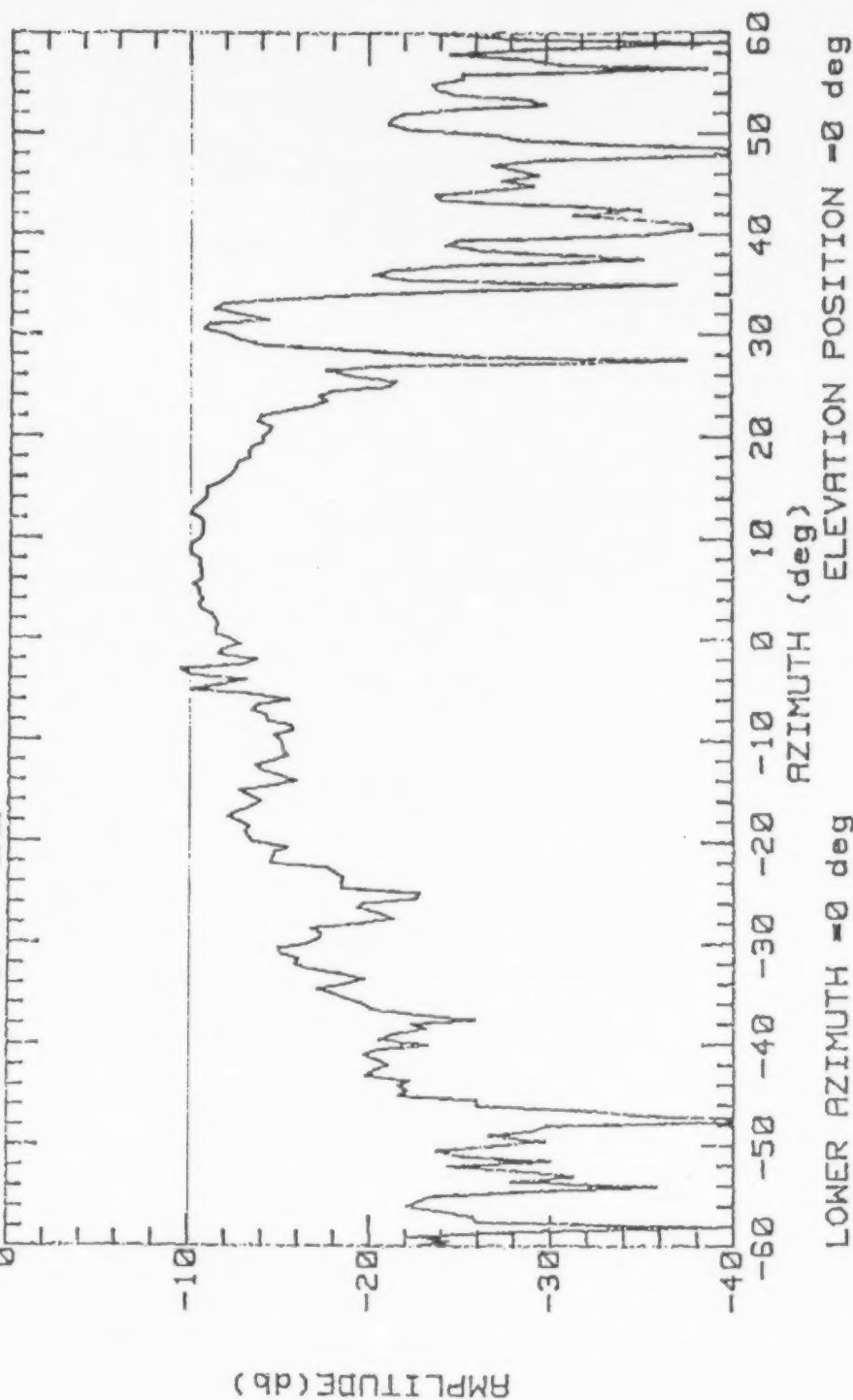
MPB TECHNOLOGIES INC. Exp.176SCAN 1 BY:L. ALLAN

ON 27 Mar 1900 16:15:37

MPB
TECHNOLOGIES INC.

MPB TECHNOLOGIES INC.
CORNER REFLECTOR MPB #100
Tx.H Rx.H GRID 0.(H) Deg.

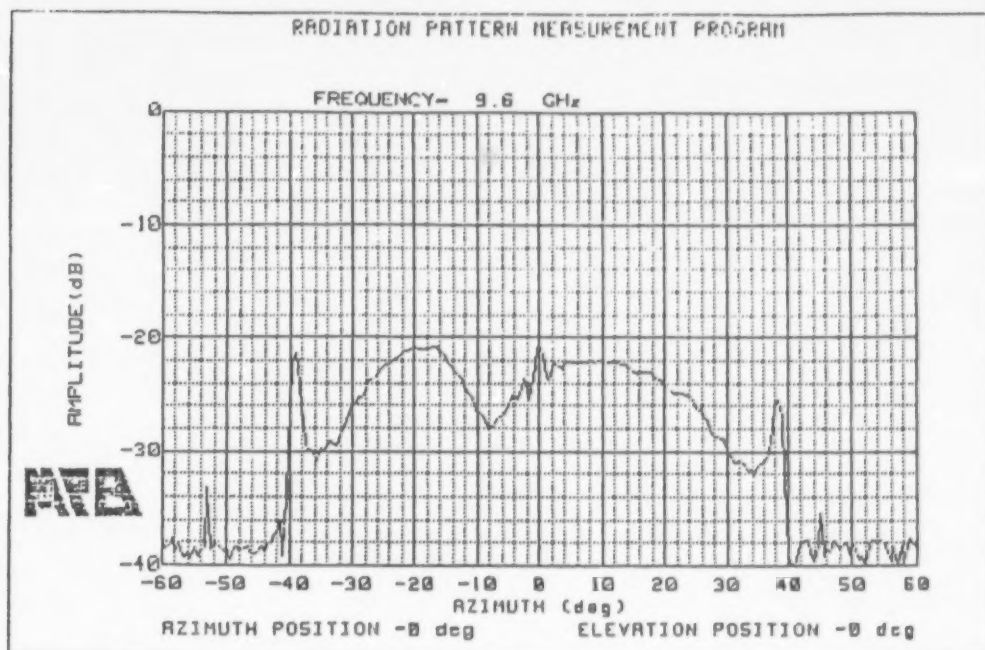
FREQUENCY = 9.4 GHz



MPB TECHNOLOGIES INC. Exp.177SCAN 1 BY:L. ALLAN

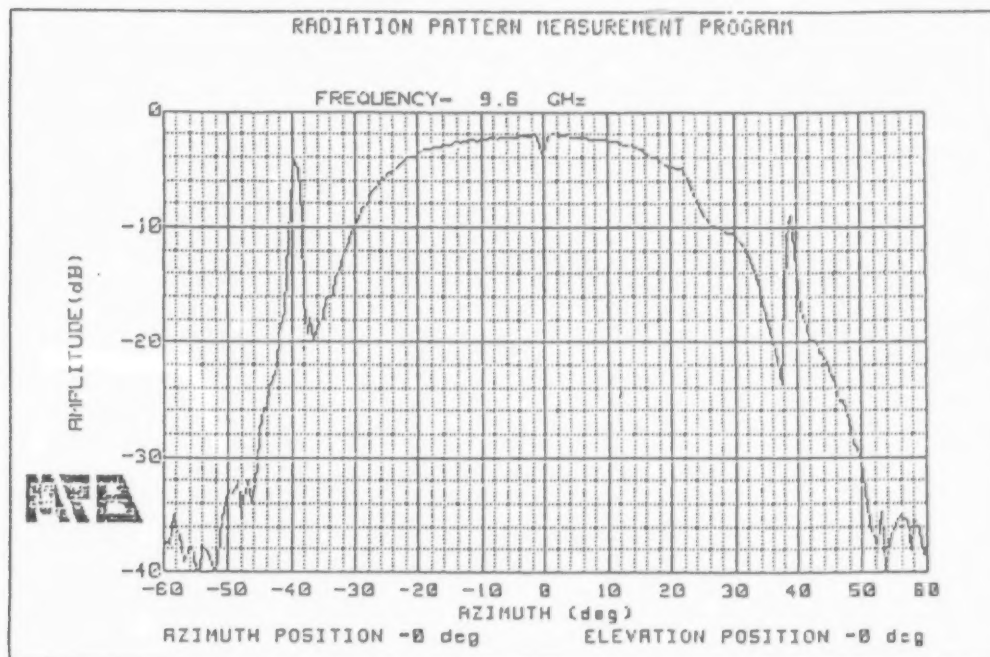
ON 27 Mar 1900 16:26:12

OUTDOOR RANGE
AT LONGER DIST. (120m)



MPB TECHNOLOGIES INC. Exp.2SCAN 1 BY:

ON 4 Jul 1988 12:13:32



MPB TECHNOLOGIES INC. Exp.2SCAN 1 BY:

ON 4 Jul 1988 12:14:54

APPENDIX

DETAILED TEST RESULTS OF LABORATORY MEASUREMENTS

1.0 Introduction

Trihedral twist grid corner reflectors reflect an incident radar signal back to the source with cross polarization. The ratio of reflected cross polarized signal to the like polarized signal is high. This is used in navigation to pinpoint targets at a distance from the transmitting antenna. A trihedral corner reflector with a twist grid was first made and tested by Cho, Haykin and Greenlay (1).

2.0 Description

The trihedral corner reflector consists of three reflecting planes so as to form a right angle corner. Figure 1 shows the one built at MPBT. Ref (2) describes the construction and properties of trihedral corner reflectors. The twist grid polarizing trihedral reflector consists of a trihedral reflector with a twist grid polarizer placed at about a quarter wavelength from one of the reflecting surfaces.

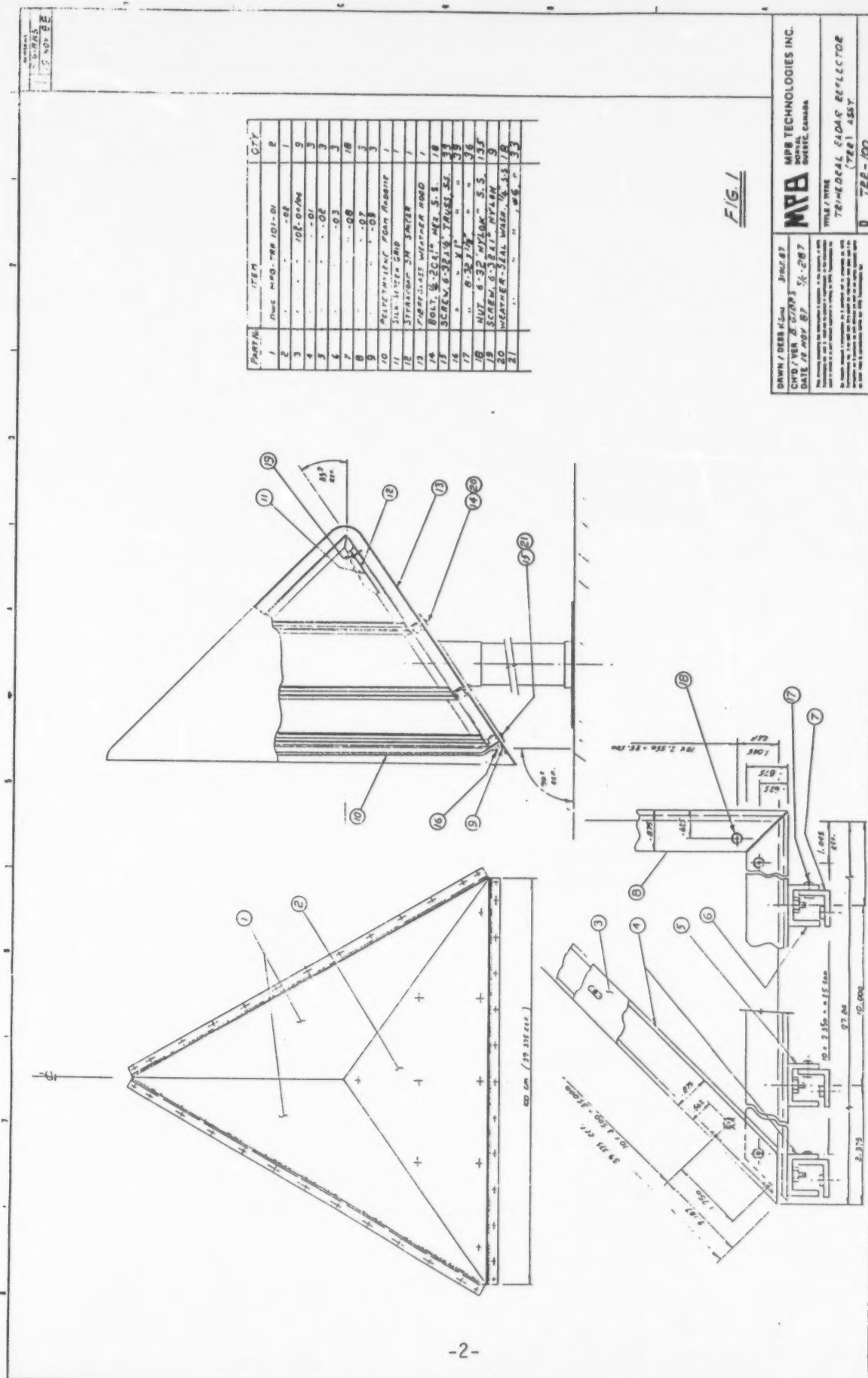


FIGURE 1: Trihedral Radar Reflector (TRR)

The twist grid consists of a coating of parallel conductive lines on a sheet of peel and stick mylar. This is glued to a low loss dielectric material such as styrofoam with a thickness of one quarter to one third of a wavelength. The lines should make an angle of 45 degrees with the polarization of the incident signal so that the signal reflected from the grid and that reflected from the plate is of equal amplitude and 180 degrees out of phase. As described in ref (1) this makes the reflected signal cross polarized. The conductive lines are coatings of silver deposited by a silkscreening process. They are 0.5 mm wide lines separated by a spacing of 5.5 mm. This grid was chosen from three grids of different spacing and line widths.

Experimental measurements as described in Section 4 were conducted to measure the transmission and reflection properties of the twist grid.

3.0 Derivation

Detailed derivation of the reflection from a polarization twist reflector has been given in Hanfling et al (3), and a patent by Hannan et al (4), and will not be reproduced here.

4.0 Experimental measurements

4.1 Transmission measurements

Experimental setup:

Figure 3 shows the experimental setup used in this measurement. It consists of a Tx horn and an Rx horn placed one meter apart and at horizontal polarization. A twist grid reflector was held at a distance of 20 cm in front of the Rx horn. An HP 8820C sweep oscillator was connected to the Tx horn and a 435A Power meter was connected to the Rx horn. The oscillator enabled measurements to be made from 9 to 10 GHz. Table 1 gives the line thickness and spacing used by the grids.

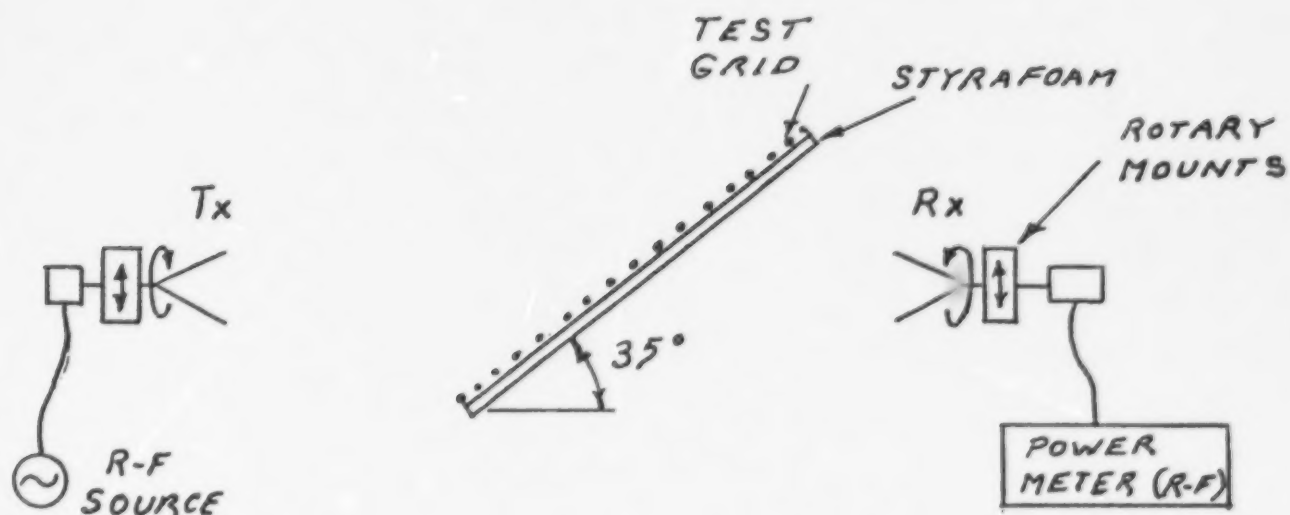


FIGURE 3: Laboratory test facility for twist-grid transmission measurements.

TABLE 1:

<u>Grid #</u>	<u>Line thickness</u>	<u>Line spacing</u>
1	0.5 mm	5.5 mm
2	1.0 mm	4.0 mm
3	0.5 mm	3.0 mm

Experimental procedure:

With this experimental arrangement the loss of transmission was measured by noting the difference in signal with and without the grid in place. First this was done at cross polarization and then with like polarization at 0 and 35 deg. tilt with respect to the beam. Table 2 gives the measured resultss.

TABLE 2:**Transmission loss measurements of twist grids**

<u>Grid #</u>	<u>Lines cross polarized to Tx</u>	<u>Lines like polarized to Tx</u>	
		<u>grid normal to beam</u>	<u>grid at 35 deg. to beam</u>
1	0.1 dB	4.5 dB	11 dB
2	0.1 dB	9.5 dB	15 dB
3	0.1 dB	13.4 dB	20 dB

CONCLUSION

As shown by Table 2, the signal is transmitted without loss when the grid is cross polarized to the signal. When the grid is like polarized the transmission loss is significant and increases as the grid spacing decreases (i.e. higher reflection). Comparing grid #1 and #3, grid #3 produces a greater loss with the grid normal to the beam because of smaller line spacing. The loss further increases as the grid is tilted back effectively decreasing the grid spacing even more.

4.2 Reflection measurements**Experimental setup:**

The experimental setup for the reflection measurement is shown in Figure 4. It consists of a Tx horn and an Rx horn mounted on lab stands with facilities to rotate the plane of polarization and tilt the horns. They were tilted down at an angle of 35 deg. with the horizontal and separated by

by 1.16m. They were mounted at 42 cm above a metal sheet kept on a table. Three nylon screws were screwed to the twist grid to enable adjustment of height above the metal sheet. The grid was kept on the metal sheet, with the lines facing the metal sheet, and in such a way that the lines make an angle of 30 deg. with the line joining the horns. This makes the angle between the line and the polarization equal to 45 degrees.

An HP 8820C sweep oscillator was connected to the Tx horn, and a 435A power meter was connected to the Rx horn. The horns were mounted so that the transmitted E vector is horizontal. The measurements were conducted at cw.

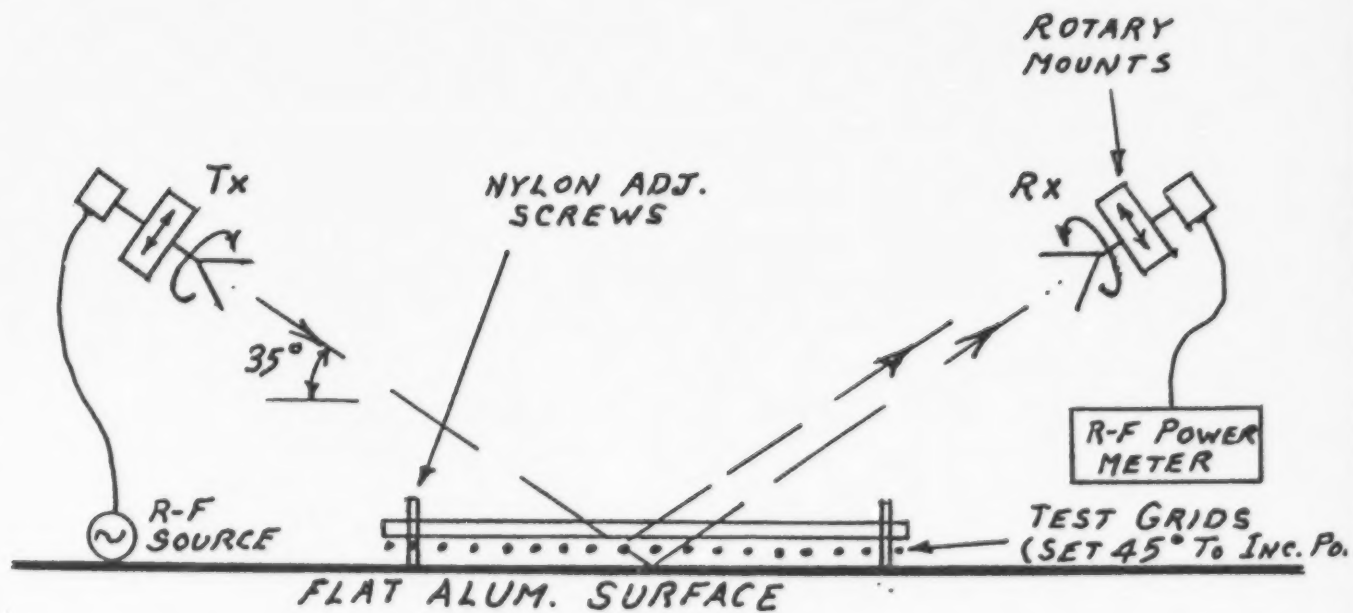


FIGURE 4: Laboratory test facility for twist-grid reflection measurements.

Experimental procedure:

To test the direct coupling between the Tx and Rx horns, an absorber was placed between them and the change in power meter reading was noted. It was found to be small.

The power meter reading was taken without the twist grid in place with the Rx horn at like polarization, and then the twist grid was placed on top of the metal sheet as mentioned above and with the lines facing the metal sheet. The distance between the grid and the metal sheet was adjusted using the nylon screws; the power meter reading was noted again. Then the Rx horn was turned about its axis by 90 degrees so that the received signal is cross polarized; the power meter reading was noted again.

This procedure was done for grid #1 and grid #3 at various spacings above the metal sheet. Most of the measurements were performed at 9.5 GHz. Table 3 lists the loss in received power level with the grid in place compared with that without the grid. The orientation of received polarization with respect to the transmit polarization is also given.

Table #3: The loss in received power level with the twist grid #3 in place with respect to that with no grid at 9.5 GHz.

Height above metal sheet	Like Polarization	Cross Polarization
1.0 cm	3.2 dB	3.6 dB
1.2	4.5	4.5
1.4	8.0	1.0
1.8	17.0	1.0
2.0	20.0	0.5
2.2	12.0	0.9
2.5	18.0	3.5
3.6	0.6	8.8
4.0	3.2	2.8
4.2	6.0	1.4
4.4	7.4	1.8
4.6	17.5	0.0
4.8	16.0	0.4
5.0	14.0	0.6
5.2	12	3.2
5.4	6.0	5.
6.0	0.6	25.0

Table 4 gives the transmission loss measured at different frequencies, for twist grid #3.

TABLE 4: The loss in received power level with twist grid #3 in place, compared with the received power level with no grid. Measurements taken at different frequencies and at a height of 2 cm.

Freq.	Height above metal sheet	Like Polarization	Cross polarization
8.0GHz	2.0cm	18.0dB	0.0dB
9.0	2.0	18.0	0.0
9.5	2.0	18.0	0.0

Grid #3 was replaced by grid #1 and the measurements were repeated. Table 5 gives the values for this case.

TABLE 5: The loss in received power level with twist grid #1 in place, compared to that with no grid. The frequency was 9.5 GHz.

Height above sheet	Like polarization	Cross metal polarization
1.0cm	8.0dB	1.7dB
1.2	11.0	1.5
1.4	18.0	0.6
1.6	19.0	0.9
1.8	12.0	1.4
2.5	2.0	8.0
2.9	0.2	26.0
3.4	1.6	7.0
4.0	8.2	0.9
4.2	16.5	0.6
4.4	22.5	0.8

The measurements were repeated for grid #1 at a wider frequency range. Table 6 gives these results.

TABLE 6: The loss in received power level with the twist grid #1 in place, compared with that with no grid. Wider frequency range was used.

Frequency	Height above metal sheet	Like polarization	Cross polarization
7.5GHz	1.8cm	-	0.6dB
7.5	2.0	-	0.6
9.0	1.4	-	0.5
10.0	1.4	-	0.5
12.0	1.1	-	0.0

CONCLUSION

The results of the above procedure in general agrees with the expected behaviour according to theory. Table 3 shows a very little loss in cross polarized signal and a large loss in the like polarized signal, at about 1.8 cm height above the metal sheet. That is the twist grid is cross polarizing the signal very efficiently at this height of grid above the metal sheet. A similar point is found at about 4.8cm. The reflected cross polarized signal goes through a series of peaks and valleys as the height is varied.

Whenever the cross polarized reflected signal is a maximum, the reflected like polarized signal is a minimum and vice versa. Table 5 shows grid #1 also behaves similarly. But Grid #1 response is less sharp compared with grid #3. This is because the lines in grid #1 are spaced apart more, and therefore the grid surface is not a well defined plane. This nature of the grid enables the grid #1 to be used for wider bandwidth and better off axis response. Table 6 confirms the wideband behaviour of grid #1. The above measurements reveal the twist grid placed at about 1.8 cm above a metal sheet is a good polarizing reflector.

5.0 Preliminary indoor reflection measurement of the MPBT twist grid trihedral reflector

Experimental setup:

The experimental setup is shown in Figure 5. This was done in the laboratory. The reflector was kept on a table with polarizing surface at the bottom and at a distance of about 5.5m from the Tx and Rx horns. The grid lines were parallel to the line joining the bottom and the left reflecting surface. The Rx horn was mounted just below the Tx horn.

An HP8820C sweep oscillator was connected to the Tx horn, and a 435C power meter was connected to the Rx horn.

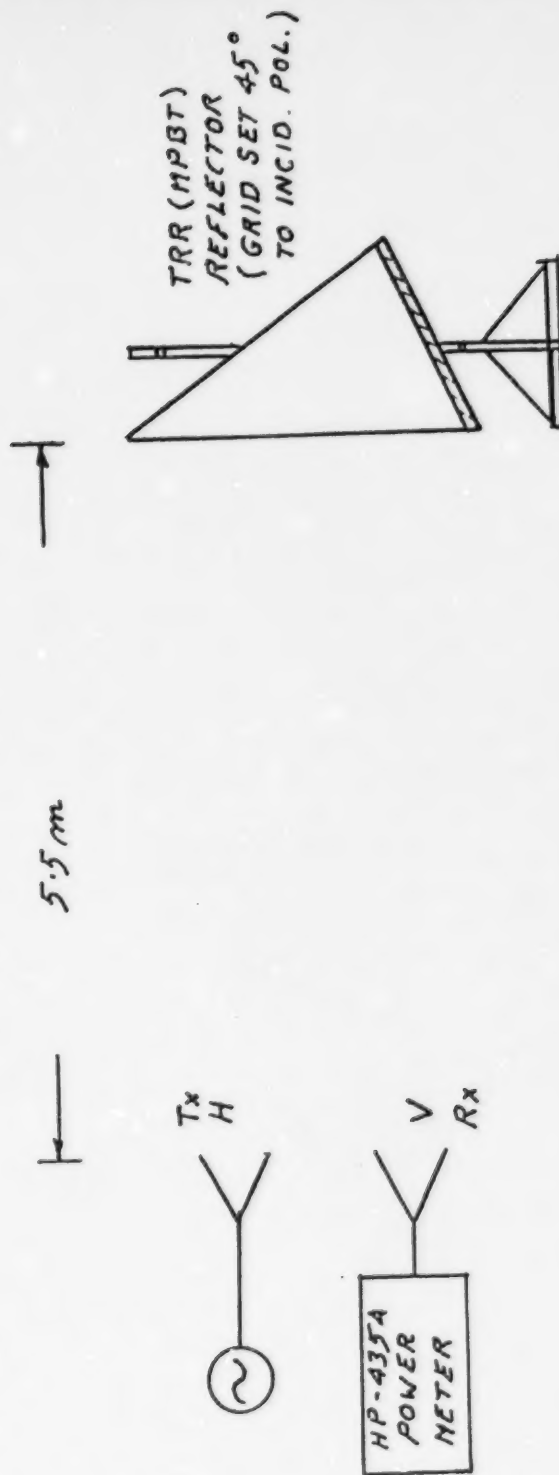


FIGURE 5: Lab test setup for preliminary measurements of Trihedral Radar Reflector.

Experimental procedure:

In order to make the angle between the direction of polarization and the grid lines equal to 45 degrees, the Tx horn was tilted such that the transmit polarization makes an angle of 15 degrees with the horizontal. First the Rx horn was mounted so that it is like polarized with respect to the Tx horn. The power meter reading was noted. Then the Rx horn was cross polarized and the reading was noted again. It was found that reflected cross polarized signal is about 7 dB higher than the reflected like polarized signal.

The reflector was removed and the reading corresponding to the background reflection was taken. It was found that the reflected cross polarized signal with the reflector, was about 20 dB higher than that with no reflector. It was about the same magnitude for like polarization.

6.0 TRR-100 MPBT Trihedral Twist Grid Reflector Measurements taken at MPBT Parking Lot.

Experimental setup:

The TRR-100 MPBT Trihedral Twistgrid Reflector was set up at MPBT parking lot as shown in Figure 6. The reflector was held against a telephone pole at a height of 4m on the stand. The stand consists of a plywood sheet with a circular hole of about one meter diameter. The reflector was fastened to a circular sheet of plywood which rotates in the circular hole. This facility allowed rotation of the reflector about the axis. Angle graduations were marked to read the angle. The whole thing was mounted on two 4m long legs. The stand was erected in position by a pulley attached to the telephone pole. This allowed adjustment of angle of boresight in the vertical plane.

As shown in Figure 6, the Transmit Receive system consists of a 56 cm long Tx horn of gain 25 dB, mounted at horizontal polarization and an Rx horn of Gain 15 dB, with facilities to adjust the polarization and the bore sight. The Tx horn also had bore sight adjustment capability. An HP8820C sweep oscillator was connected to a HUGHES 1177N TWT amplifier through a 6 dB attenuator. An HP 435A power meter was connected to the Rx horn.

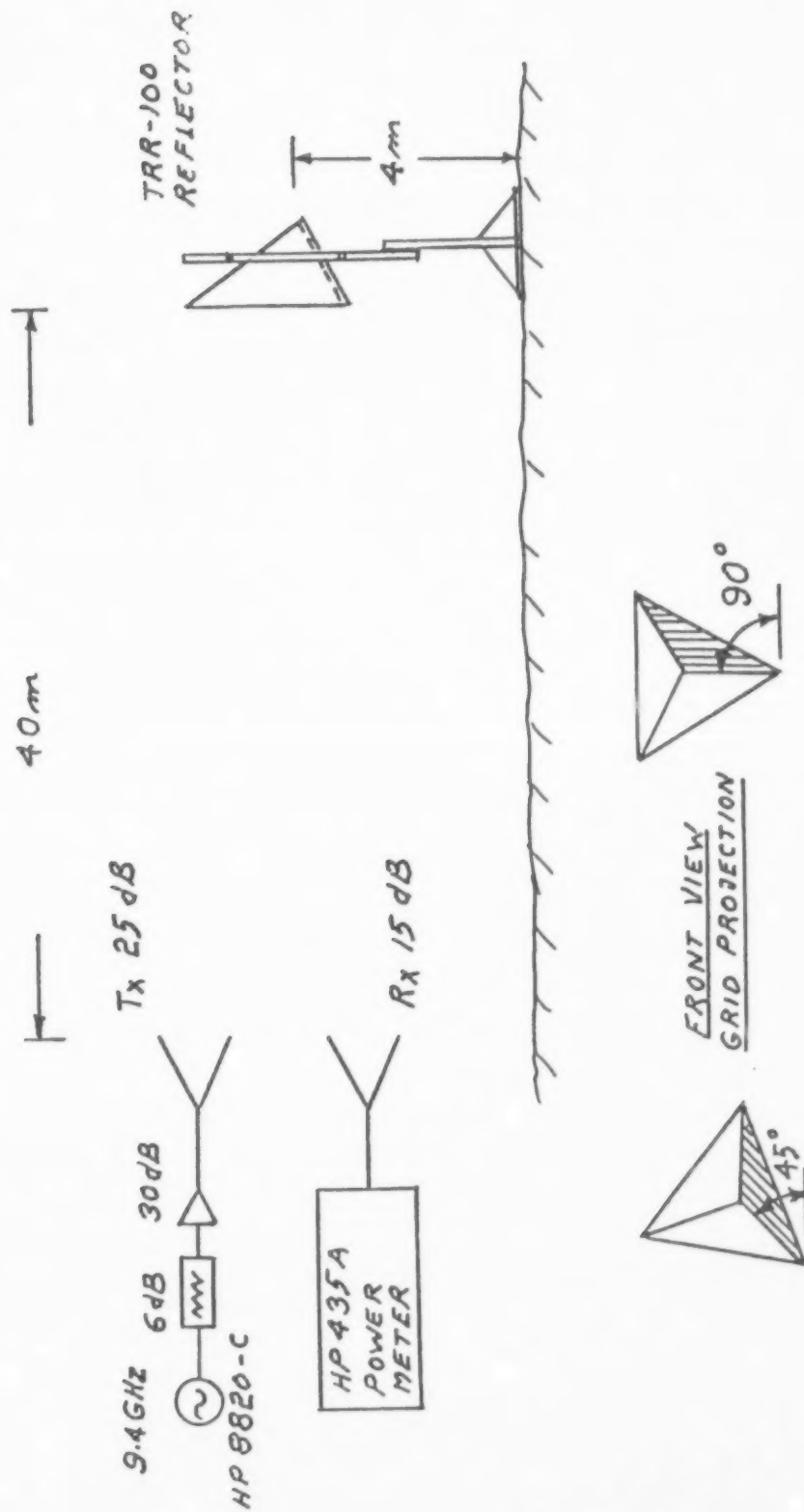


FIGURE 6: Preliminary field test of Trihedral Radar Reflector in MPBT parking lot.

Experimental procedure:

The transmit receive system was placed at the warehouse door facing the reflector. The door was sealed from cold weather by a low loss foam. The distance between the reflector and the transmit receive system was 41m. The sweep oscillator was set at 9.4 GHz cw. Table 7 shows the power meter readings taken as a function of polarization, direction of grid lines and presence or absence of reflector. The Tx horn was at horizontal polarization throughout the experiment.

TABLE 7: Received power meter readings as a function of polarization, direction of grid lines and presence or absence of reflector. Note that the direction of grid lines indicate the angle made by the projection of grid lines on a plane normal to the Tx bore sight.

Presence of reflector	Rx poln.	Direction of grid	Power meter readings dBm
yes	vert.	45 deg.	-27 to -27/5
yes	horiz.	45	-37 to -40
no	horiz.	45	-40 to -45
no	vert.	45	-55 to -65
yes	horiz.	90	27 to -28
yes	vert.	90	-55 to -65

CONCLUSION

Comparing received power levels for vertical and horizontal polarization, the vertical polarization is about 10 to 12 dB higher than the horizontal polarization. This confirms that the twist grid reflector reflects the signal with cross polarization.

REFERENCES

- (1) Polarimetric Radar for Precise Navigation. (PRAN) R. Cho, S. Haykin and T. Greenlay, McMaster University, TP7632E, Apr. 1986.
- (2) Passive Retro-Reflectors for use with Precise Radar Navigatgion Systems, T. Greenlay and S. Haykin, CRL Report, CRL-117, Apr. 1983.
- (3) Twist Reflector Design Using E-Type and H-Type Modes, Hanfling et al, IEEE Trans. Ant. & Prop. Vol. AP-29, No.4, July 1981.
- (4) Twist Reflector, Hannan et al, US Patent Application 3,161,879, Jan.5, 1961, Ser.No. 80,961.

APPENDIX C

Dual-Polarized Antenna
Factory Acceptance Test

F. A. T. R E P O R T

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TO BE USED AS TEST PROTOCOL

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CHRISTIAAN HUYGENSLABORATORIUM B.V.

ACCEPTANCE TEST REPORT

Project : Dual Polarized Antenna

Order ~~Number~~ : FAX of 30 juli 1987

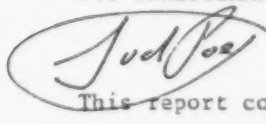
Date : 12 april 1988

Acceptance test report for the equipment, specified on Page 3.

Accepted :

For OFFSHORE SYSTEMS LTD.

For CHRISTIAAN HUYGENSLABORATORIUM B.V.

 S.H. van der Poel
This report consists of 29 pages.

ACCEPTANCE TEST REPORT

Project : Dual Polarized Antenna
Order ~~Number~~ : FAX of 30 juli 1987
Date : 12 april 1988

Specification of the equipment

Radar antenna system type SHV-30-B, consisting of:

- ° Slotted waveguide antenna type SHV-30-B
Serial number : 01-8803
- ° Gearbox type : CM20 4D71
Serial number : 401 801 989-1-1
- ° Two-channel rotating joint type: X-2K
serial number : 4-23 M
- ° Motor type : FN 71
Serial number : 786 763
- ° Incremental hollow shaft encoder type: COI60050A
Serial number : 160 - 87
SPARE : 160 - 86

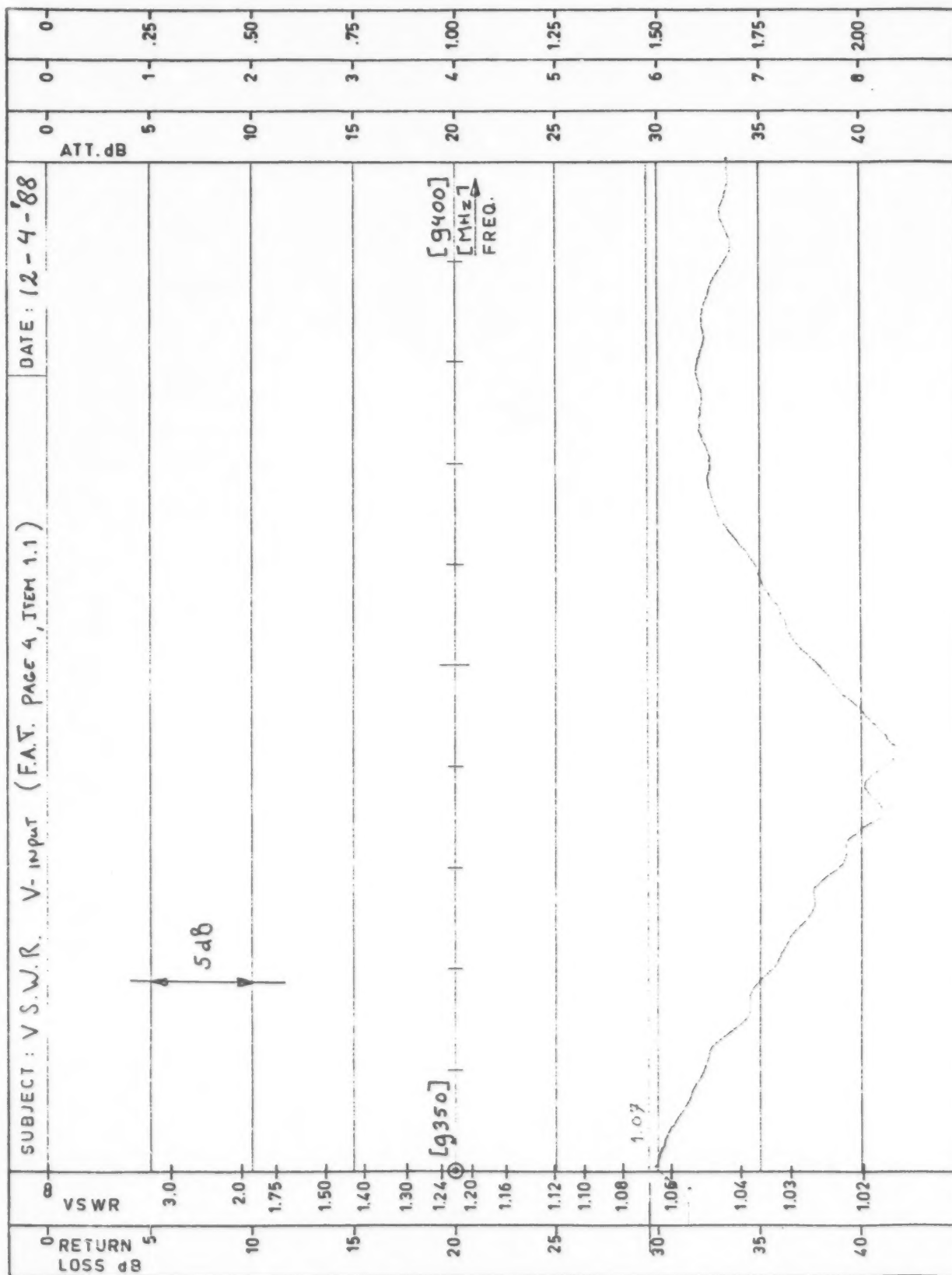
ACCEPTANCE TEST REPORT - ANTENNA SYSTEM

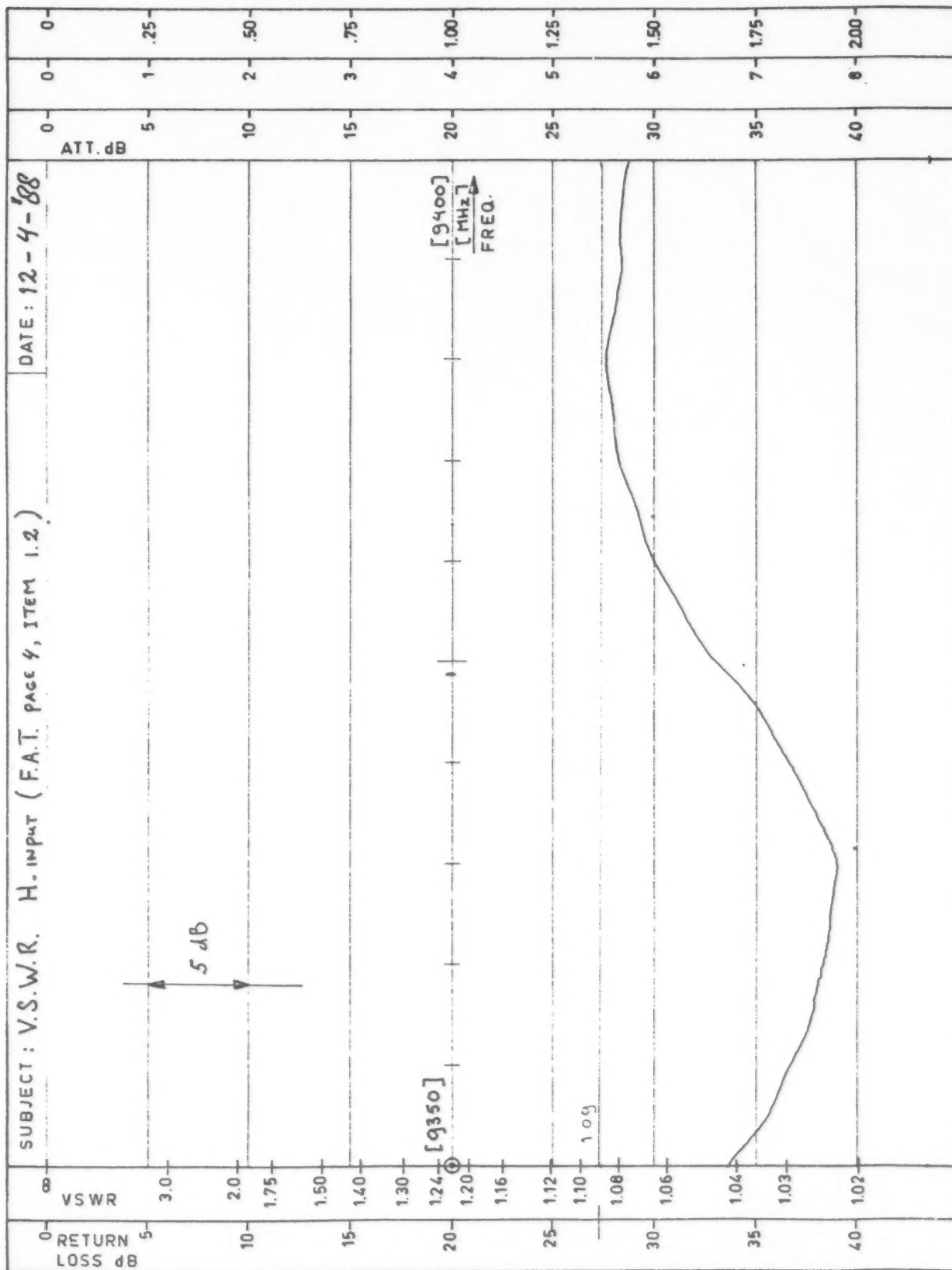
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 Antenna type : SHV-30-B Polarization : Vertical/Horizontal
 Serial number :
 A. Antenne measurements

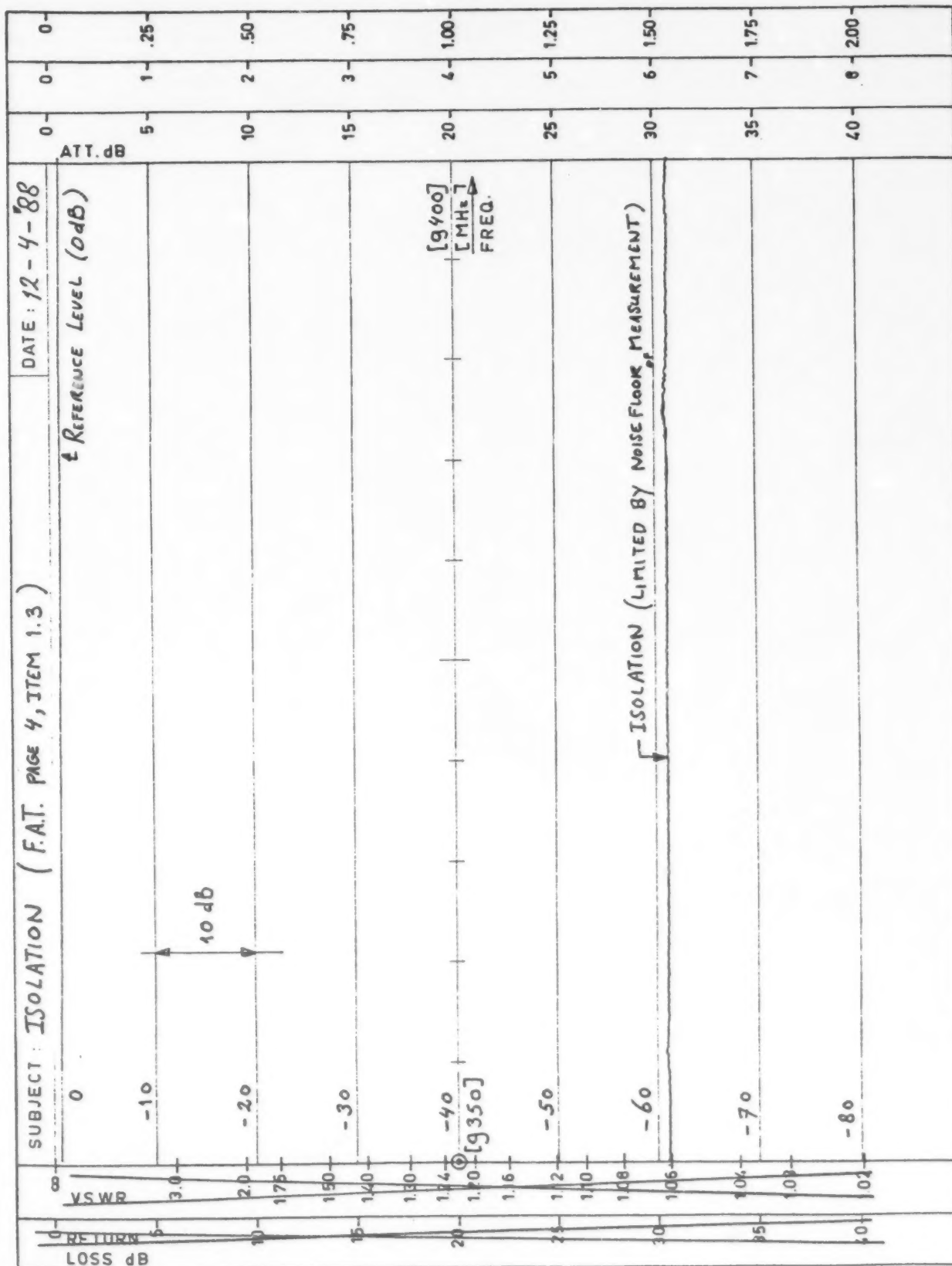
Number	Description	Requirement	Measured Factory
1.	V.S.W.R. measured at the input of the rotating joint, for frequency band: 9350-9400 MHz	max. 1.30 : 1	< 1.07
1.1	Vertical input		< 1.09
1.2	Horizontal input		
1.3	Isolation between both polarizations, antenna plus rotating joint	< -30 dB	< -60
2.	<u>Azimuth radiation pattern</u>		
2.1.	Horizontal beamwidth for elevation $\theta=0^\circ$ and vertical/horizontal polarization respectively.		
2.2.1	At (-3 dB) points		0.97 / 0.93
	9350 MHz V/H		0.94 / 0.91
	9375 MHz V/H	$1.0^\circ \pm 0.1^\circ$	0.93 / 0.92
	9400 MHz V/H		
2.1.2	At (-20 dB) points		2.31 / 2.21
	9350 MHz V/H		2.31 / 2.17
	9375 MHz V/H	$2.2 \pm 0.3^\circ$	2.29 / 2.14
	9400 MHz V/H		
3.	<u>Sidelobes levels in the Azimuth Radiation Pattern</u>		
3.1	At elevation $\theta=0^\circ$		-31.6 / -28.7
	9350 MHz V/H		-32.3 / -28.8
	9375 MHz V/H		-31.3 / -27.7
	9400 MHz V/H	max. -26 dB	

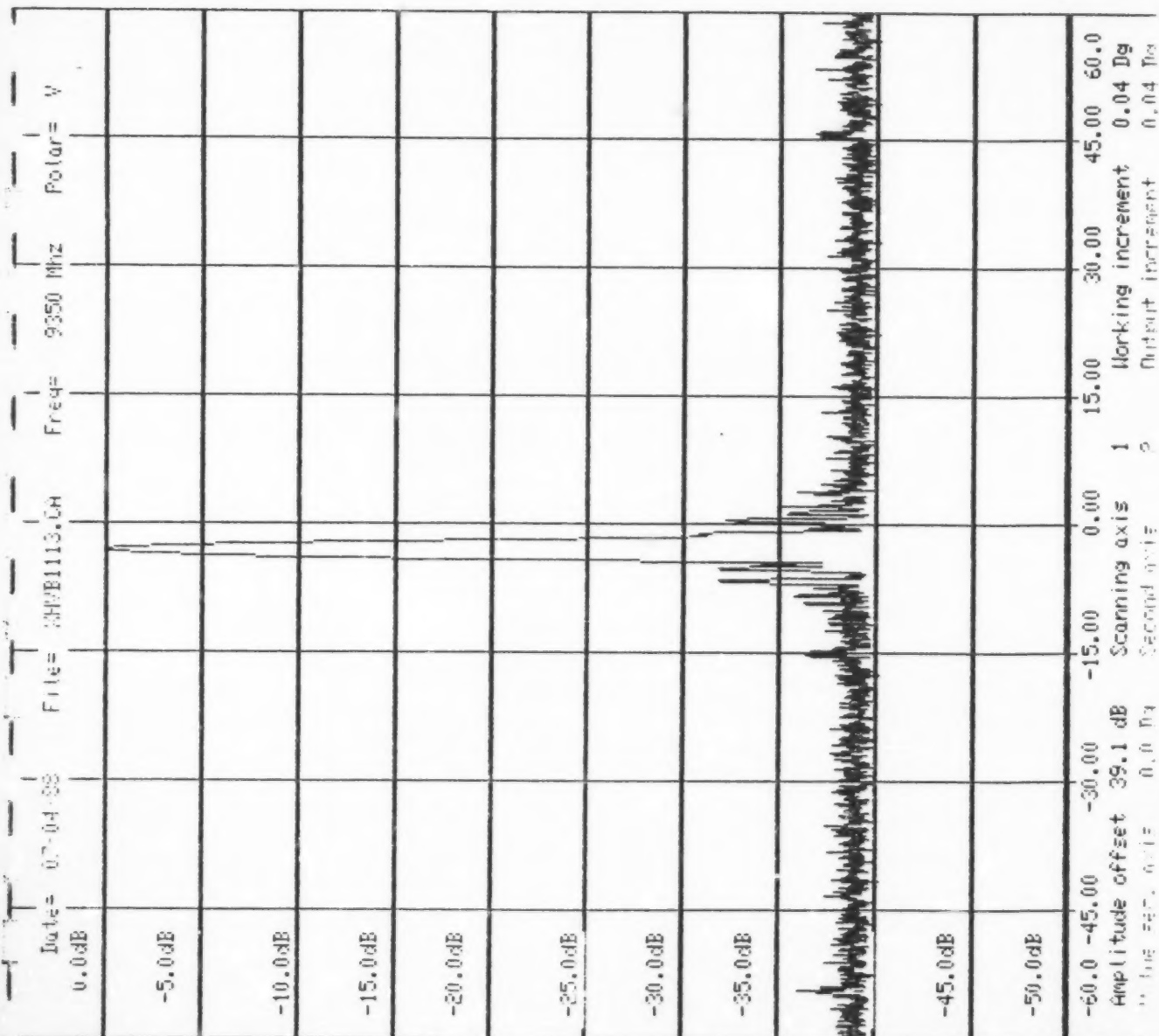
Number	Description	Requirement	Measured Factory
4.	<u>Elevation radiation pattern</u>		
4.1	Vertical beamwidth at azimuth boresight angles. Vertical/horizontal polarization respectively.		
4.1.1	At (-3 dB) points		18.1 / 18.4
	9350 MHz V/H	18.0°±2.0°	18.2 / 18.1
	9375 MHz V/H		18.0 / 18.4
	9400 MHz V/H		
4.2.1	At (-10 dB) points		34.2 / 34.4
	9350 MHz V/H	36.0°±4.0	34.1 / 34.0
	9375 MHz V/H		34.3 / 34.3
	9400 MHz V/H		
5.	<u>Antenna gain</u>		
5.1	Measured in the direction of max. value of the radiation pattern at frequency 9375 MHz gain	> 31.5 dB	32.4
	at Vertical input		32.7
	at Horizontal input		
6.	<u>Squint main lobe vs. frequency</u>	≤ 4.0°	-2.98 / -2.95
	at 9350 MHz V/H		-3.20 / -3.15
	at 9375 MHz V/H		-3.40 / -3.35
	at 9400 MHz V/H		
7.	<u>Radiation patterns</u>	(see attached diagram)	
7.1	Horizontal radiation patterns for:		
7.1.1	Elevation angle $\theta=0^\circ$ and azimuth angles: $-60^\circ \leq \phi \leq +60^\circ$		8
	9350 MHz V/H	present and attached	8
	9375 MHz V/H		8
	9400 MHz V/H		
7.1.2	Elevation angle $\theta=0$ and azimuth angles $-180^\circ \leq \phi \leq 180^\circ$		8
	9375 MHz V/H	P&A	
7.2	Vertical radiation pattern for azimuth angles at boresight. Elevation angles $-50^\circ \leq \theta \leq 20^\circ$		8
	9350 MHz V/H	P&A	8
	9375 MHz V/H		8
	9400 MHz V/H		8

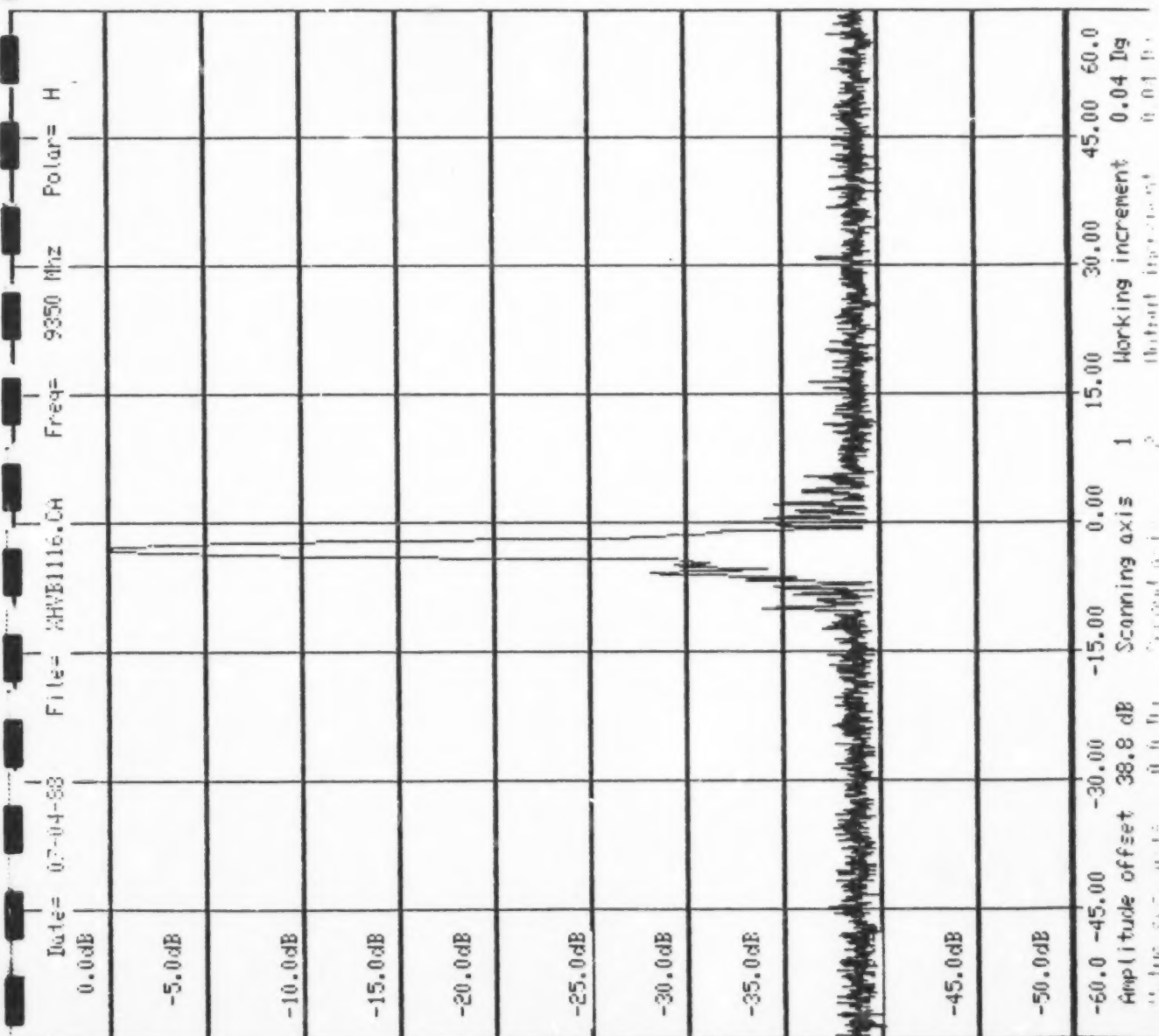
Number	Description	Requirement	Measured Factory
8.	<u>Antenna gearbox</u>		
8.1	Rotation speed with mounted antenna. Mains: 460 V (star connected) and <u>60 Hz</u> nominal	24±2 rev/min	50 Hz 60 Hz 20.3 ⇒ 24.4
8.2	Isolation motor winding to gearbox housing	≥10 M ohm	100.
8.3	Power consumption gearbox		190. WATT
9.	<u>Azimuth-encoder</u>		
9.1	Number of pulses/one: revolution <u>SPARE</u>	4096p/360°	4096 / 4096 4096 / 4096
10.	<u>Visual inspection</u>	O.K. (S)	S
10.1	Mechanical Damage	No damage which endager performance, life or utility	S
10.2	Quality of painting		S
10.3	Configuration	° Serial Numbers present. ° Serial Numbers of parts, matching those stated in protocol. ° Changes, in accordance with customer, are incorporated in the technical specifications, test documentation and in the status of the spare parts.	S S S
10.4	Documentation	Complete and transferable to OFFSHORE SYSTEMS LTD.	S

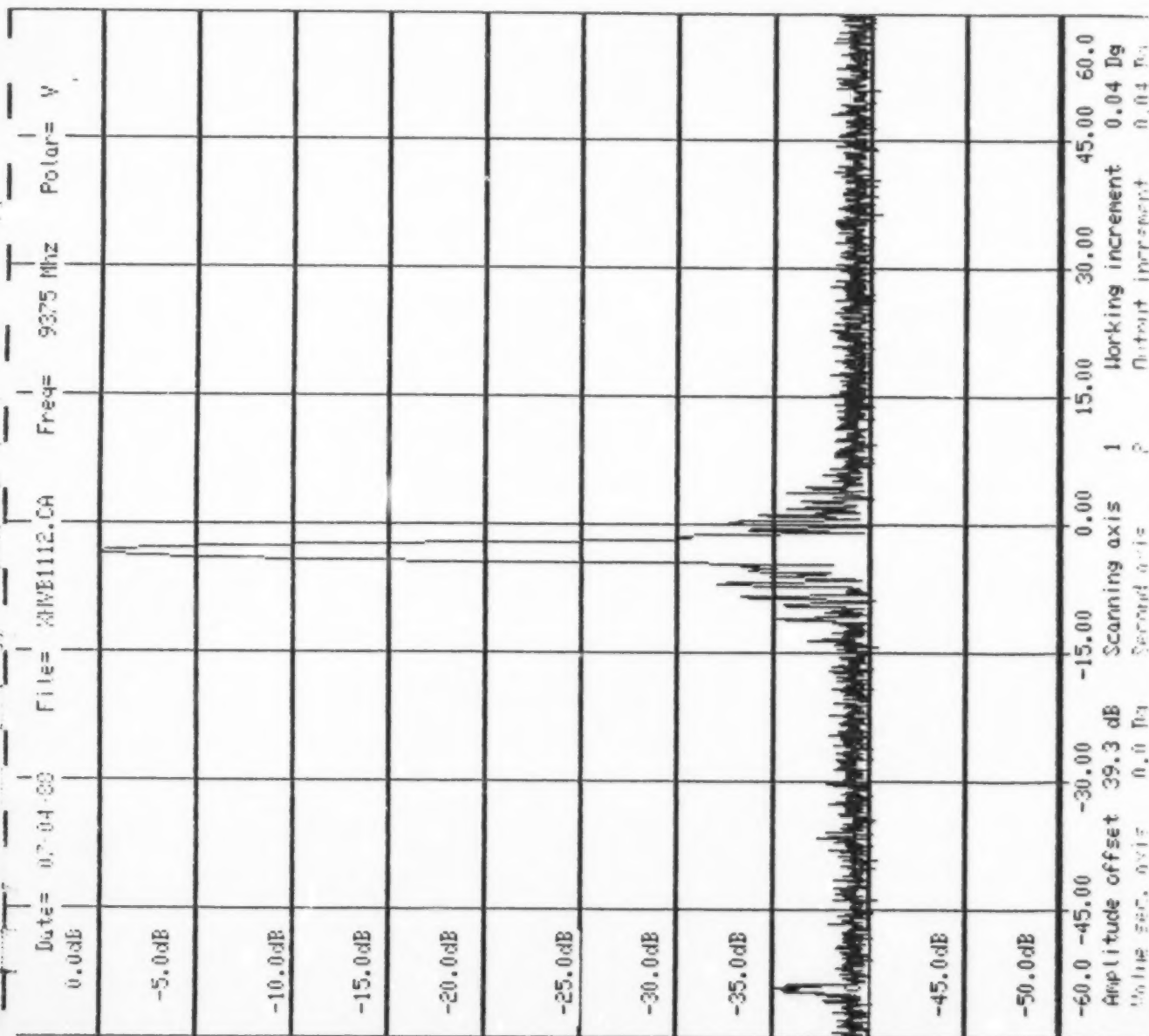


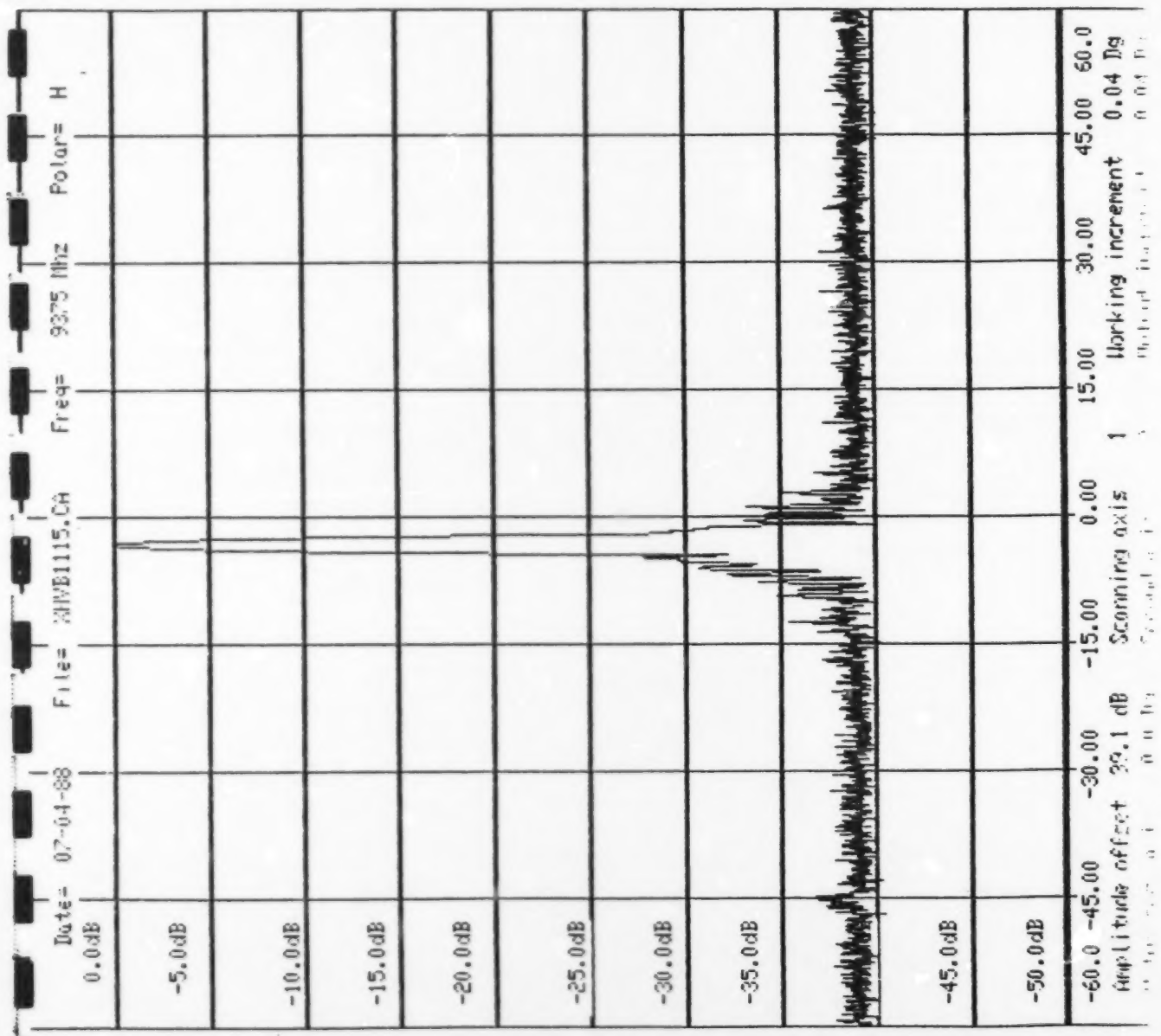


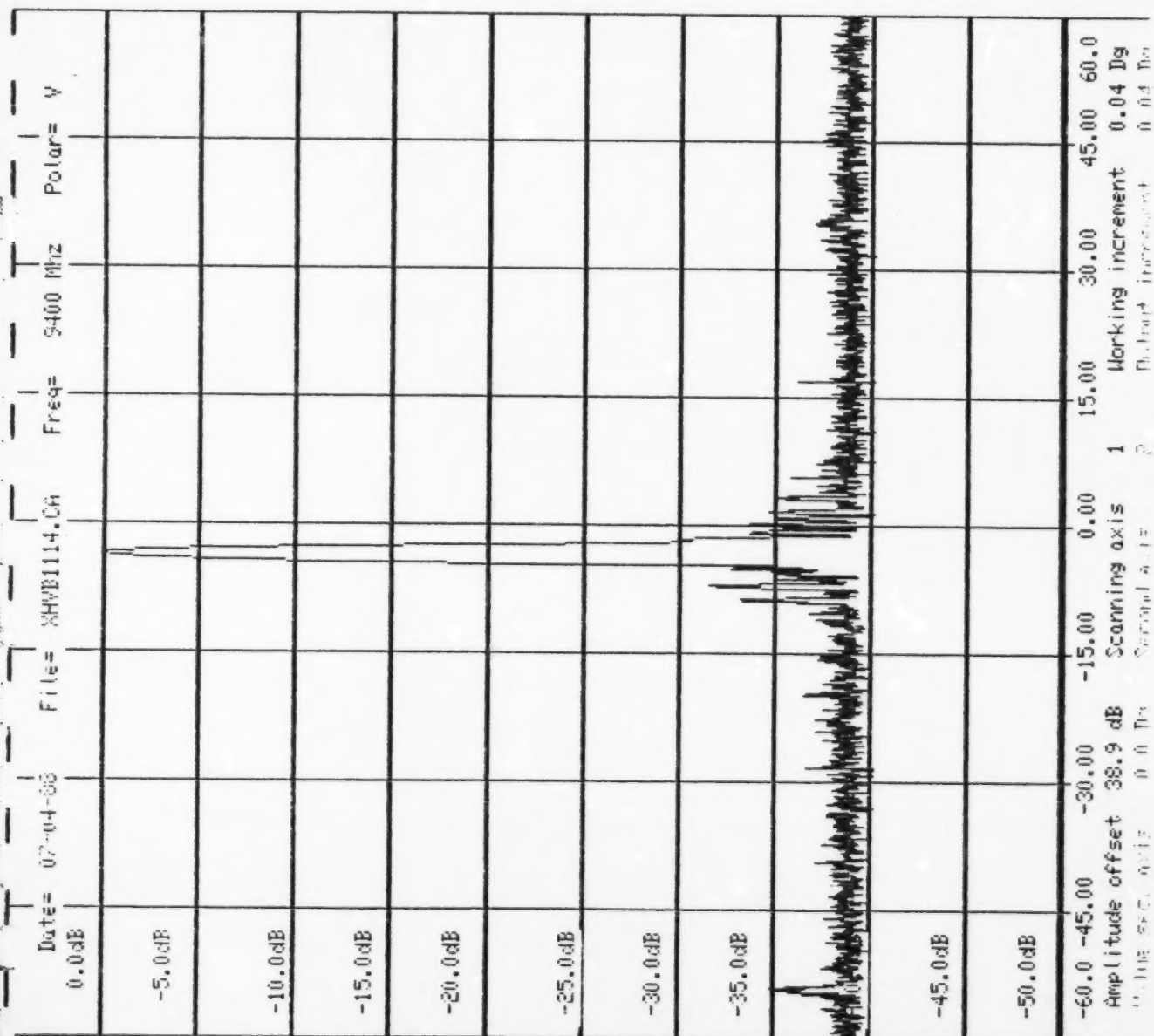




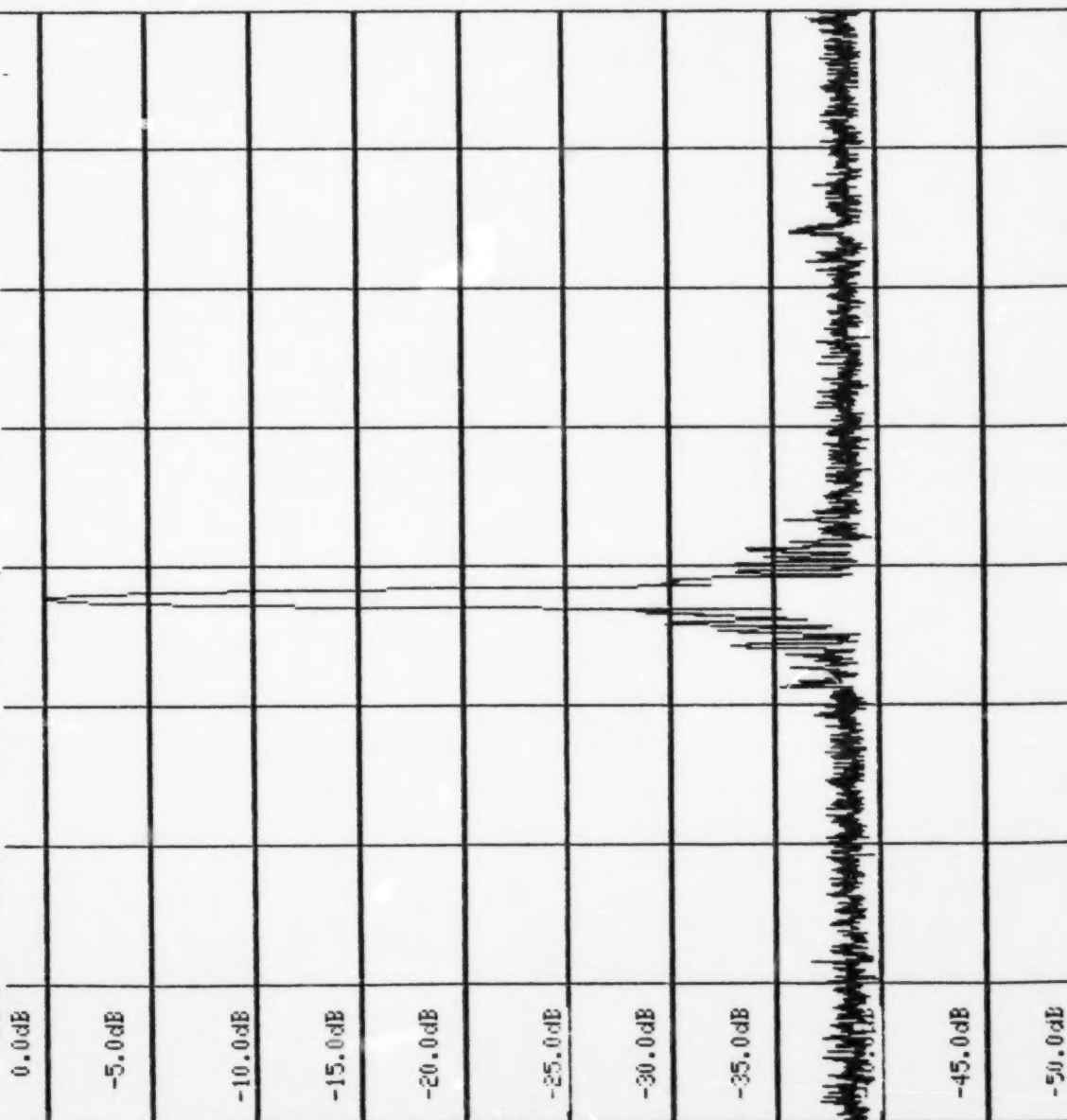




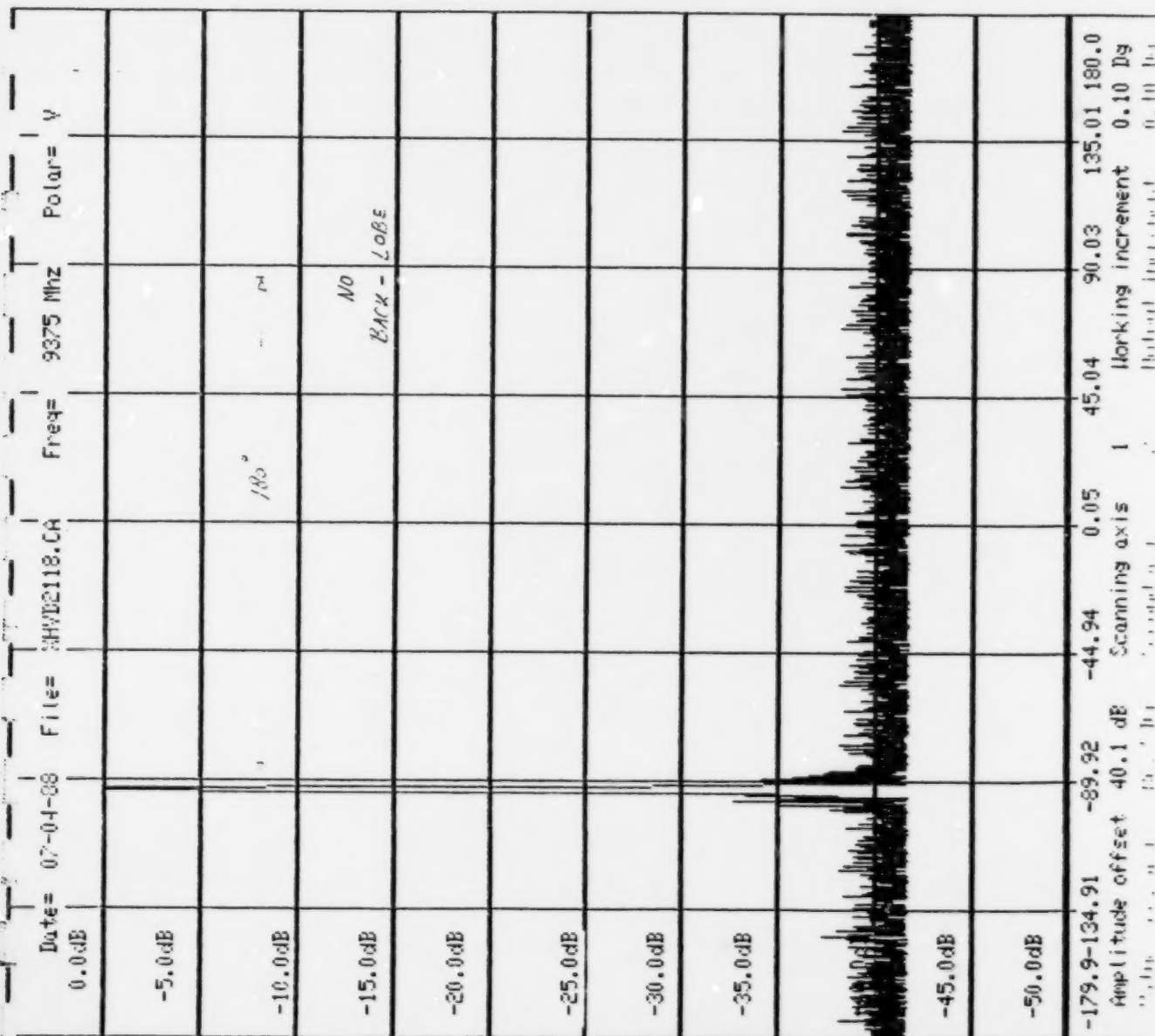




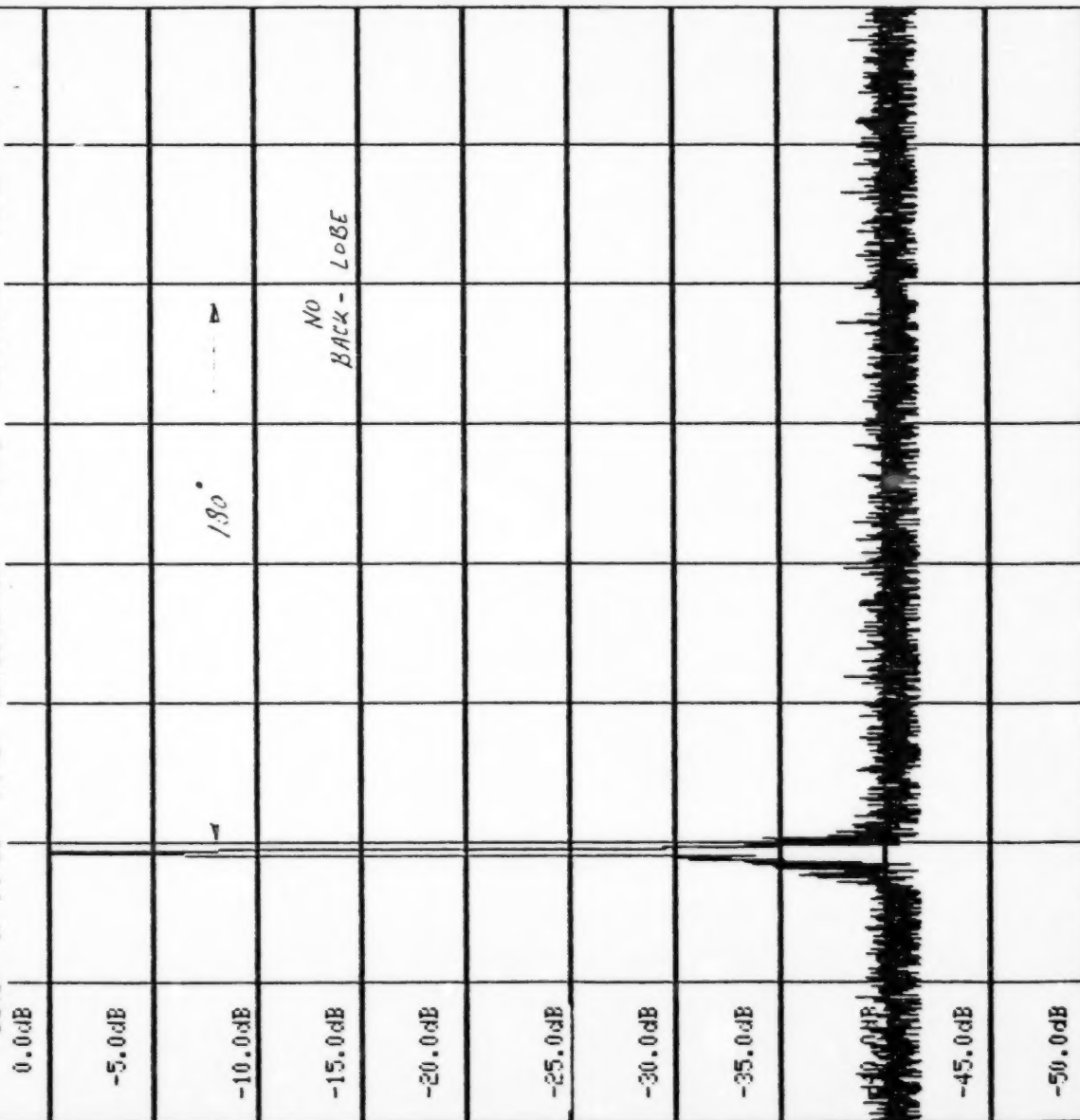
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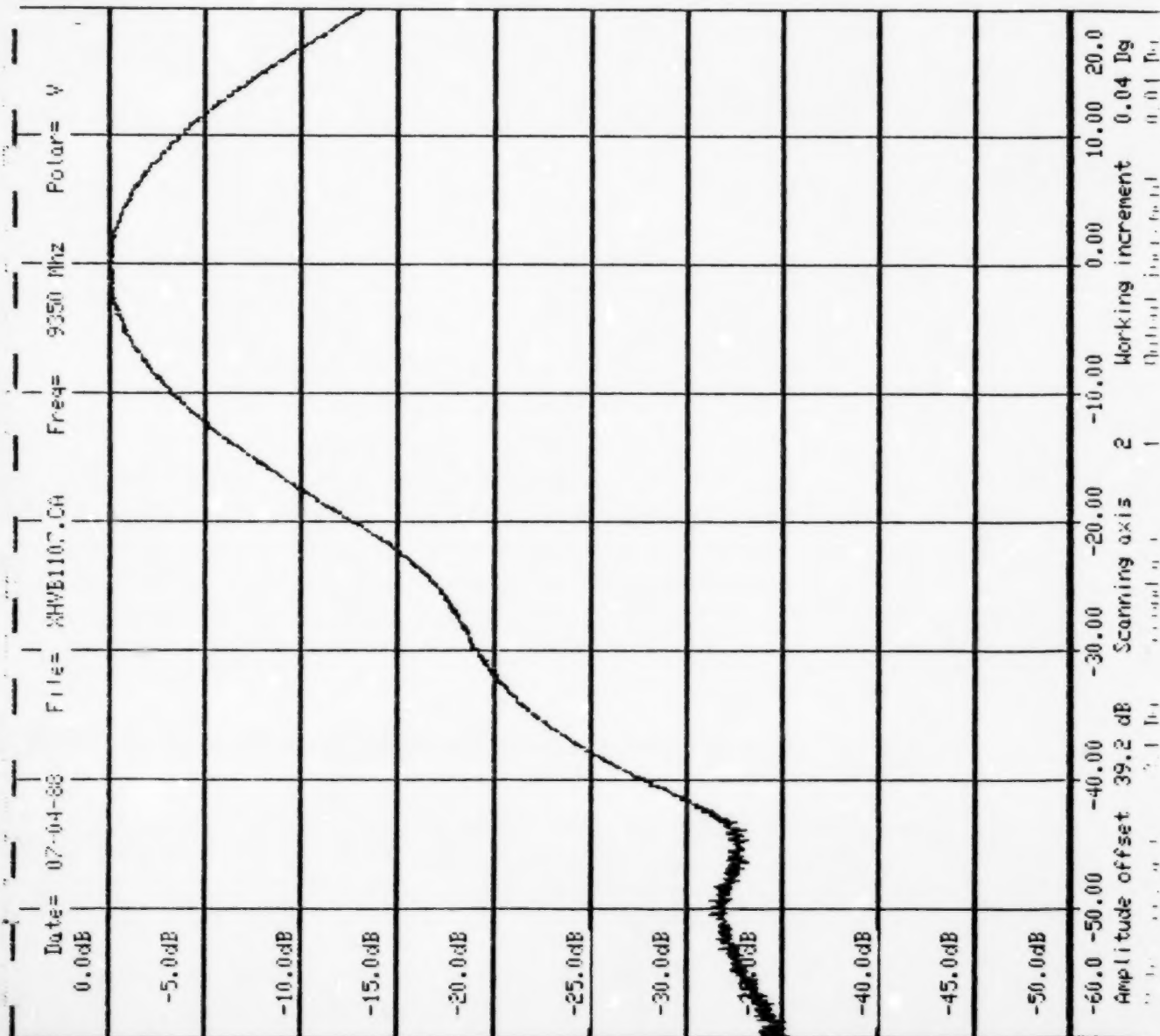
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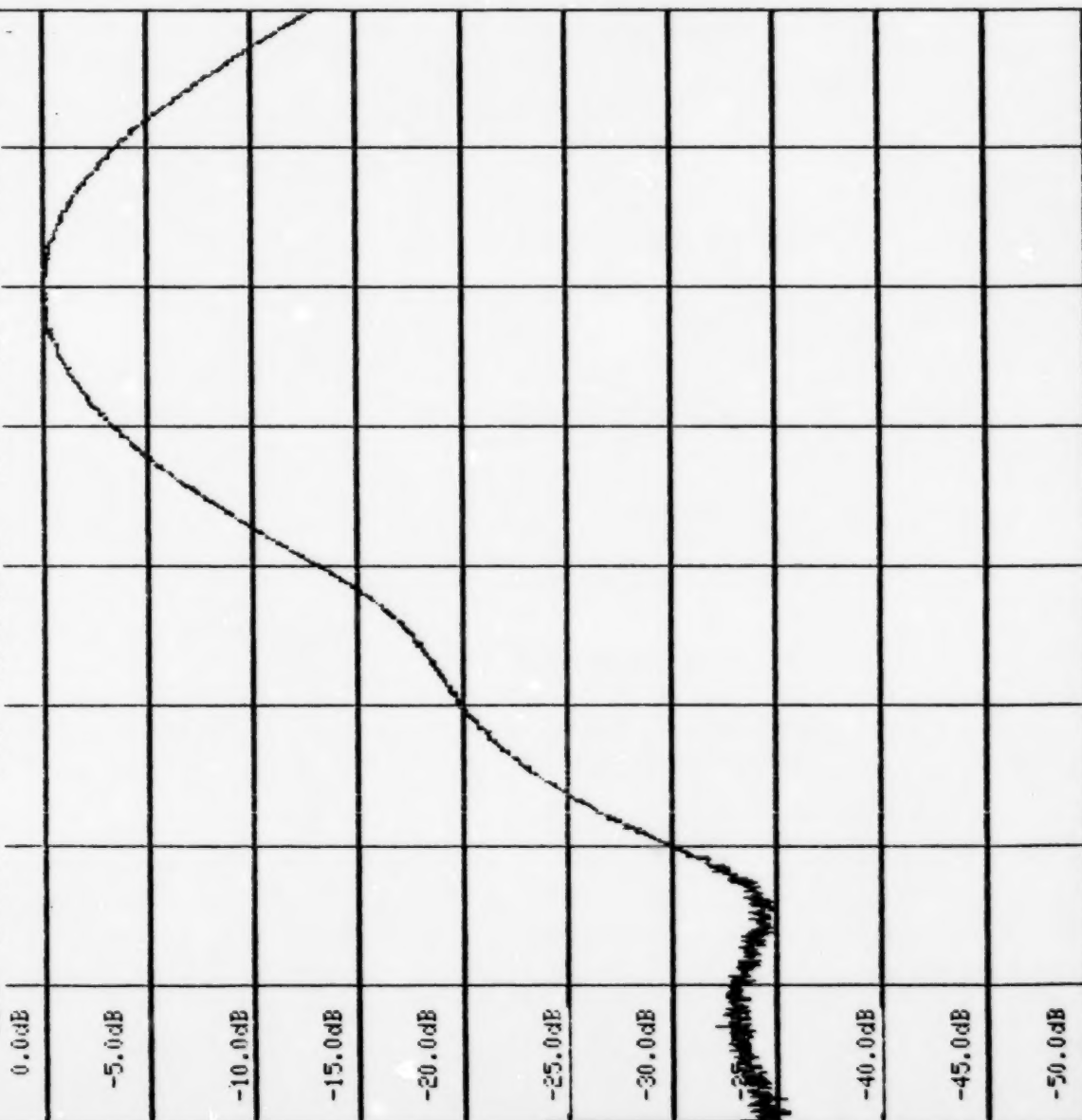
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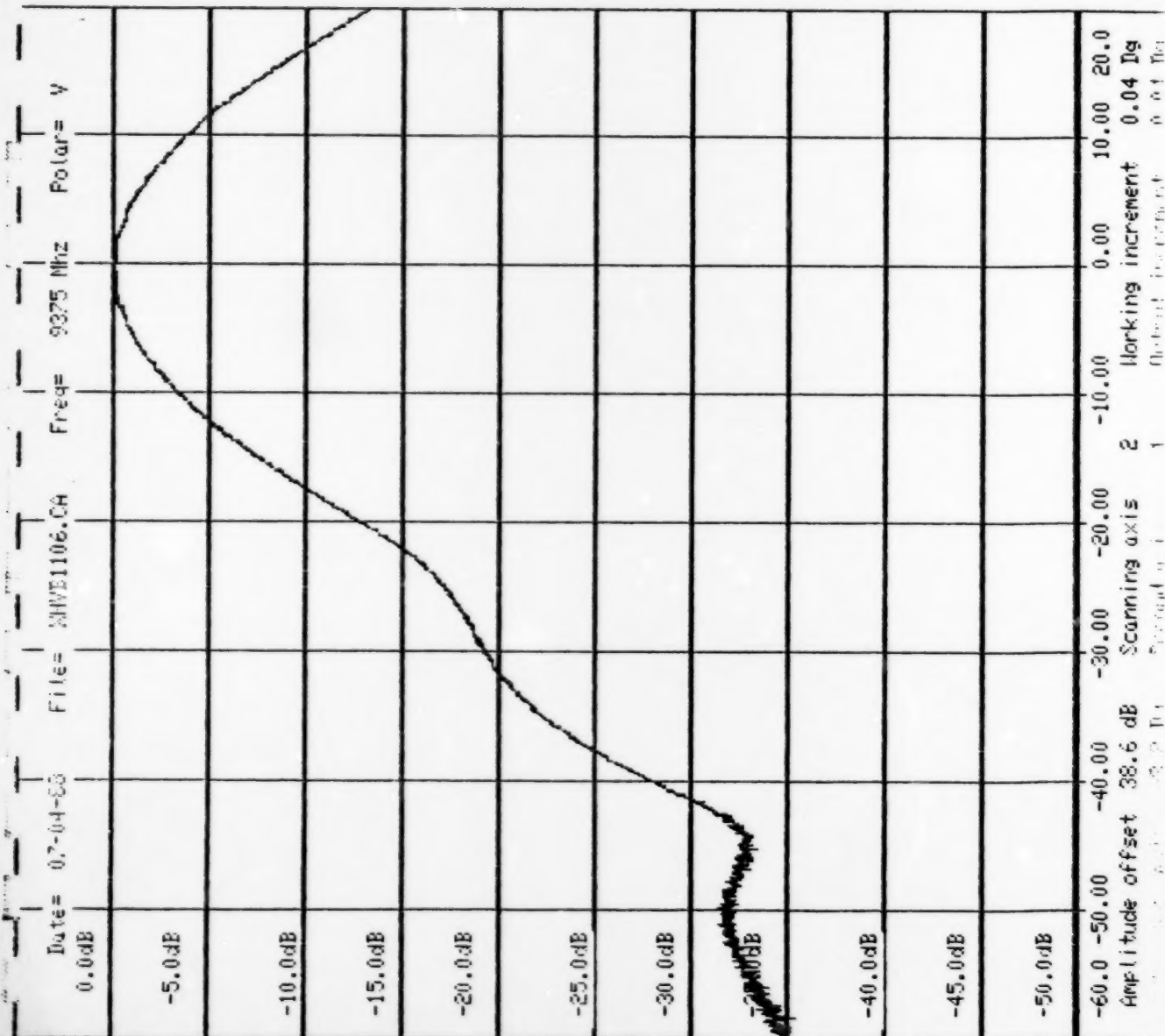
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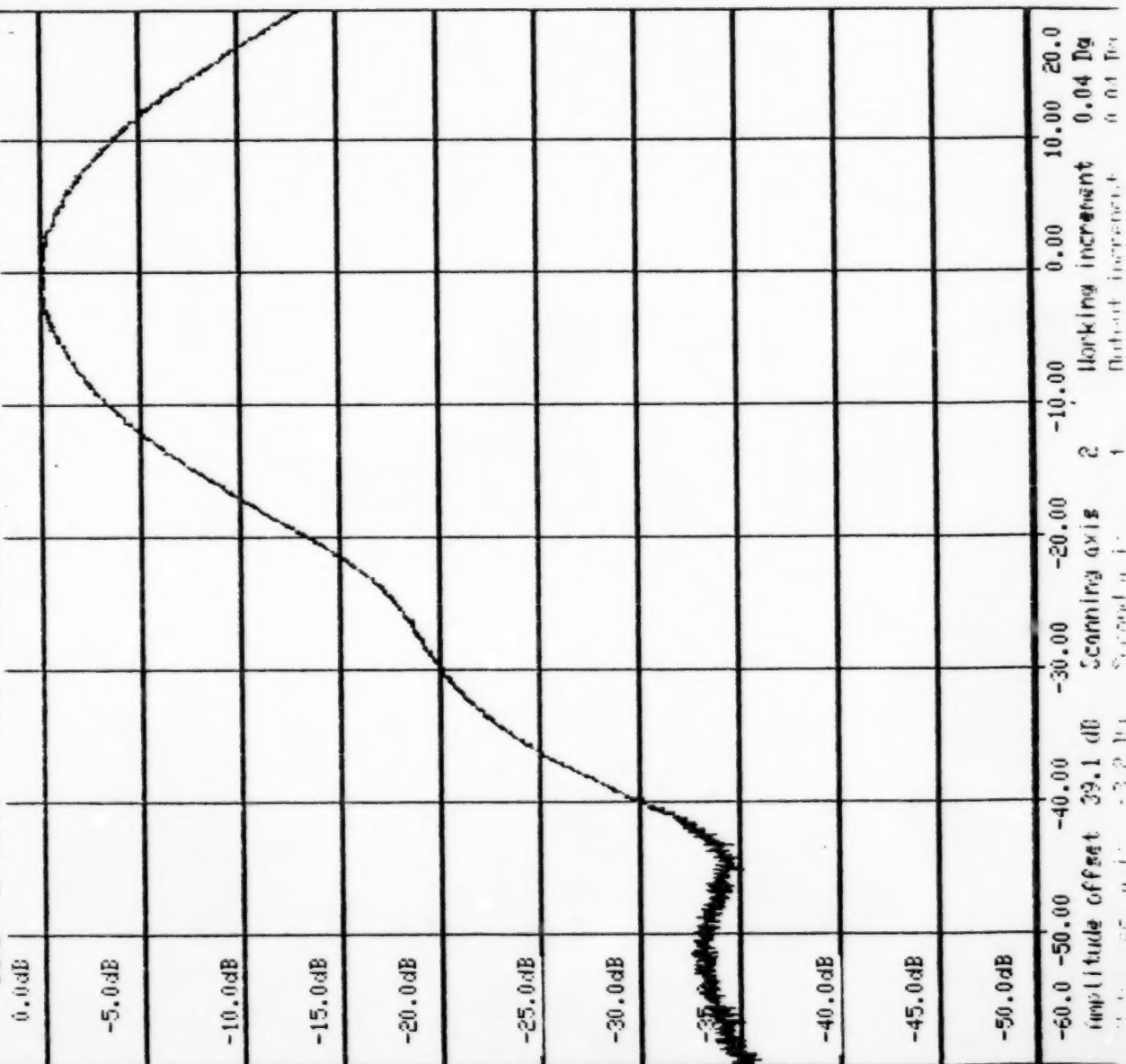
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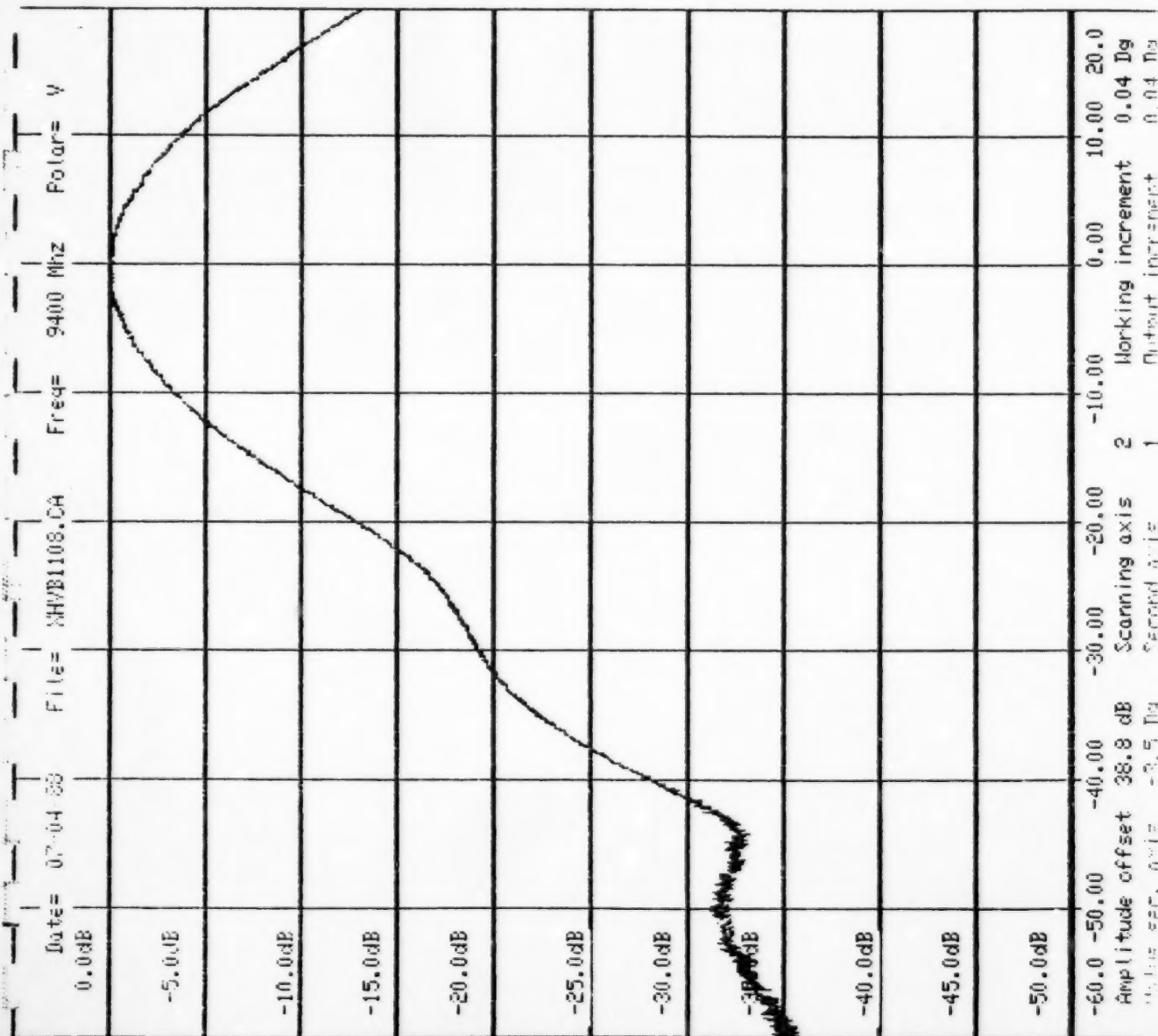
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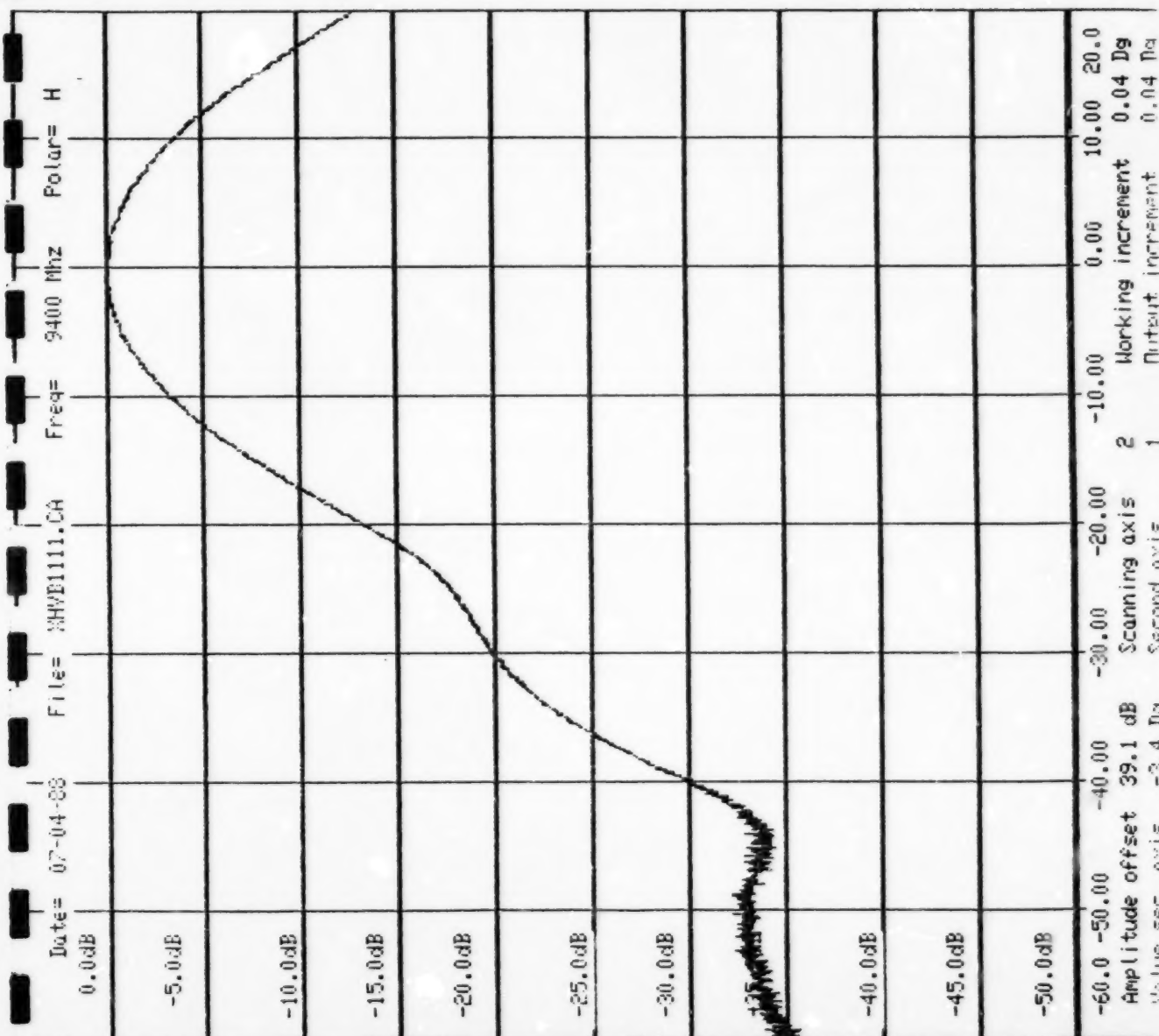


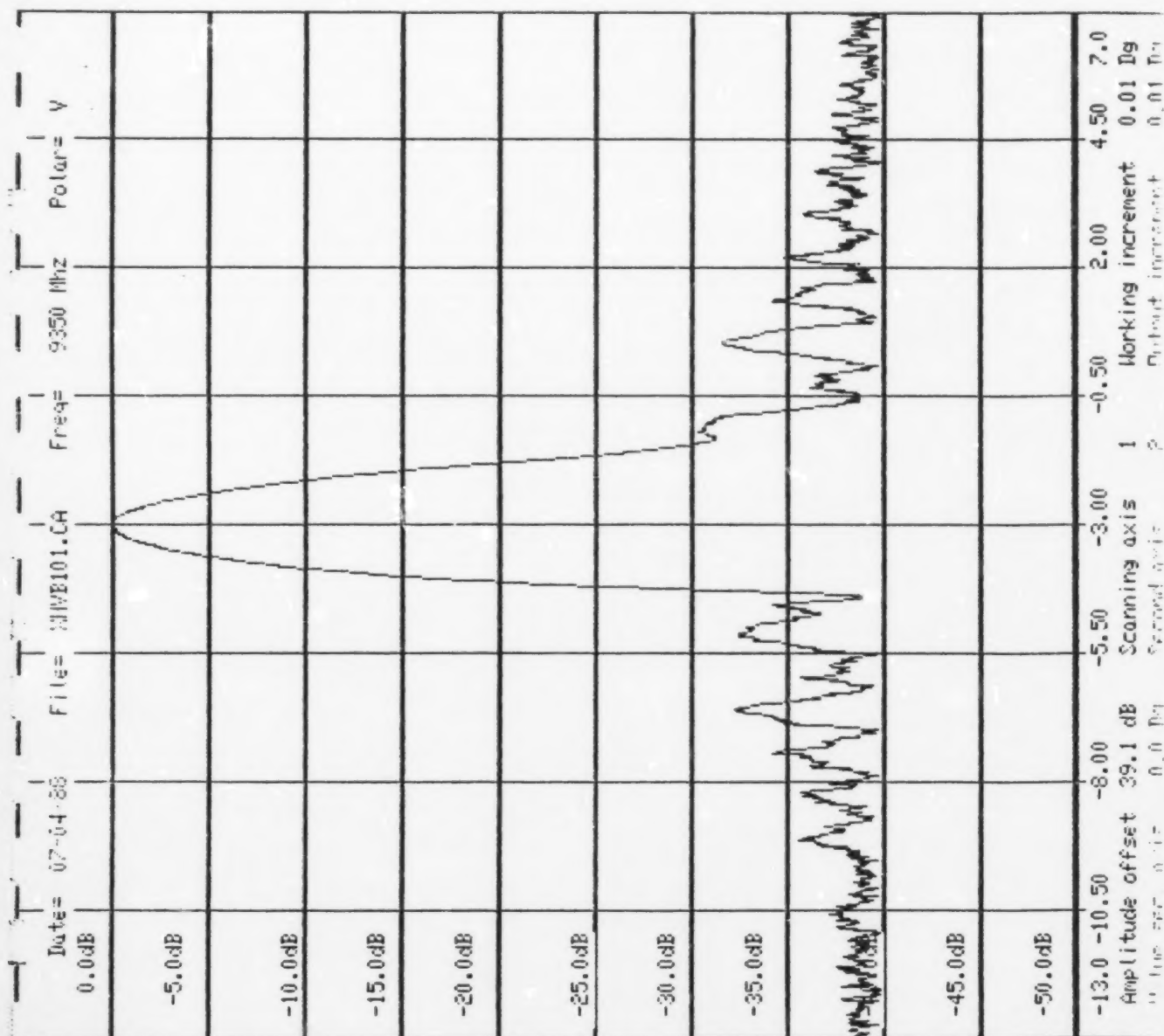
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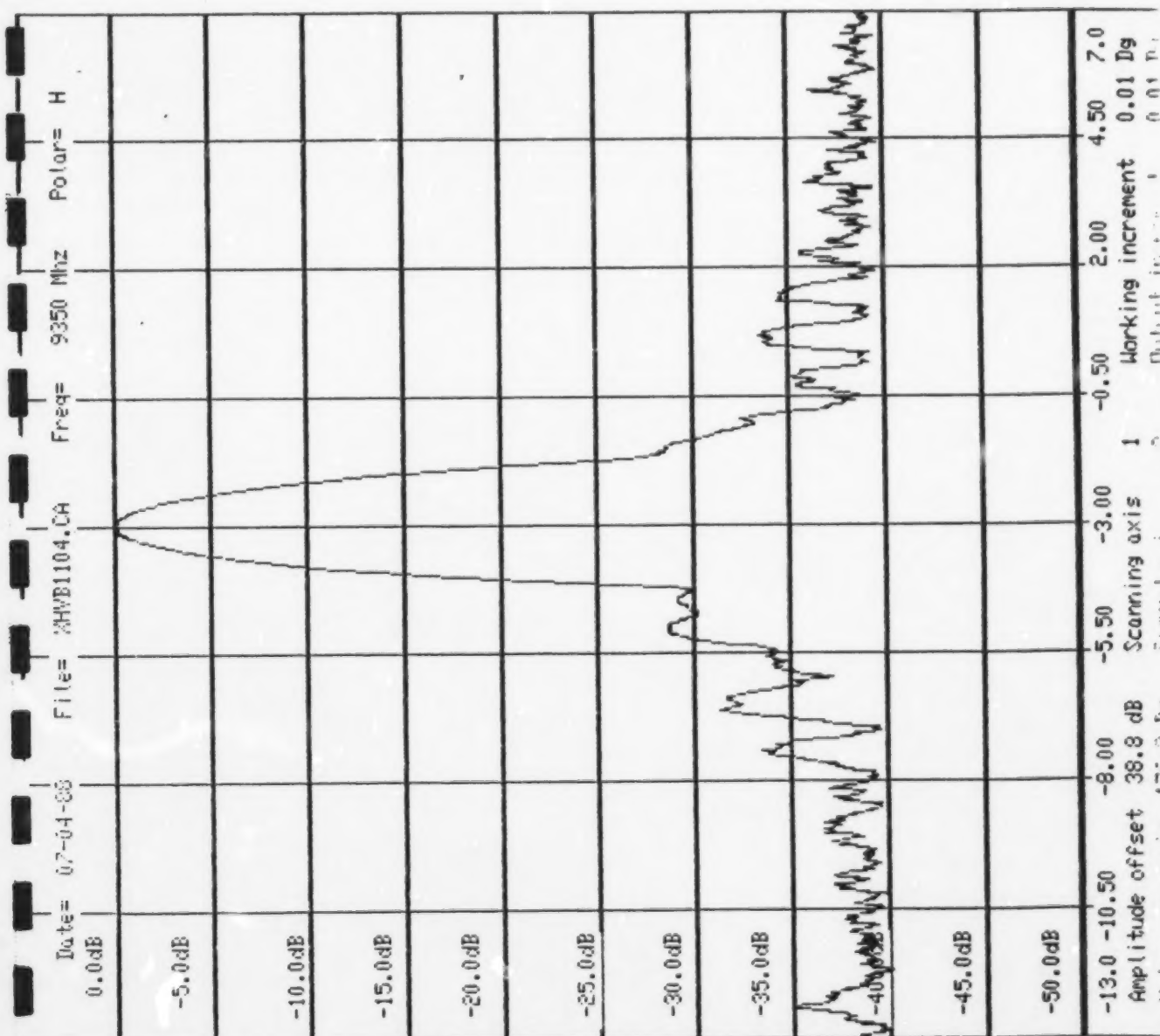


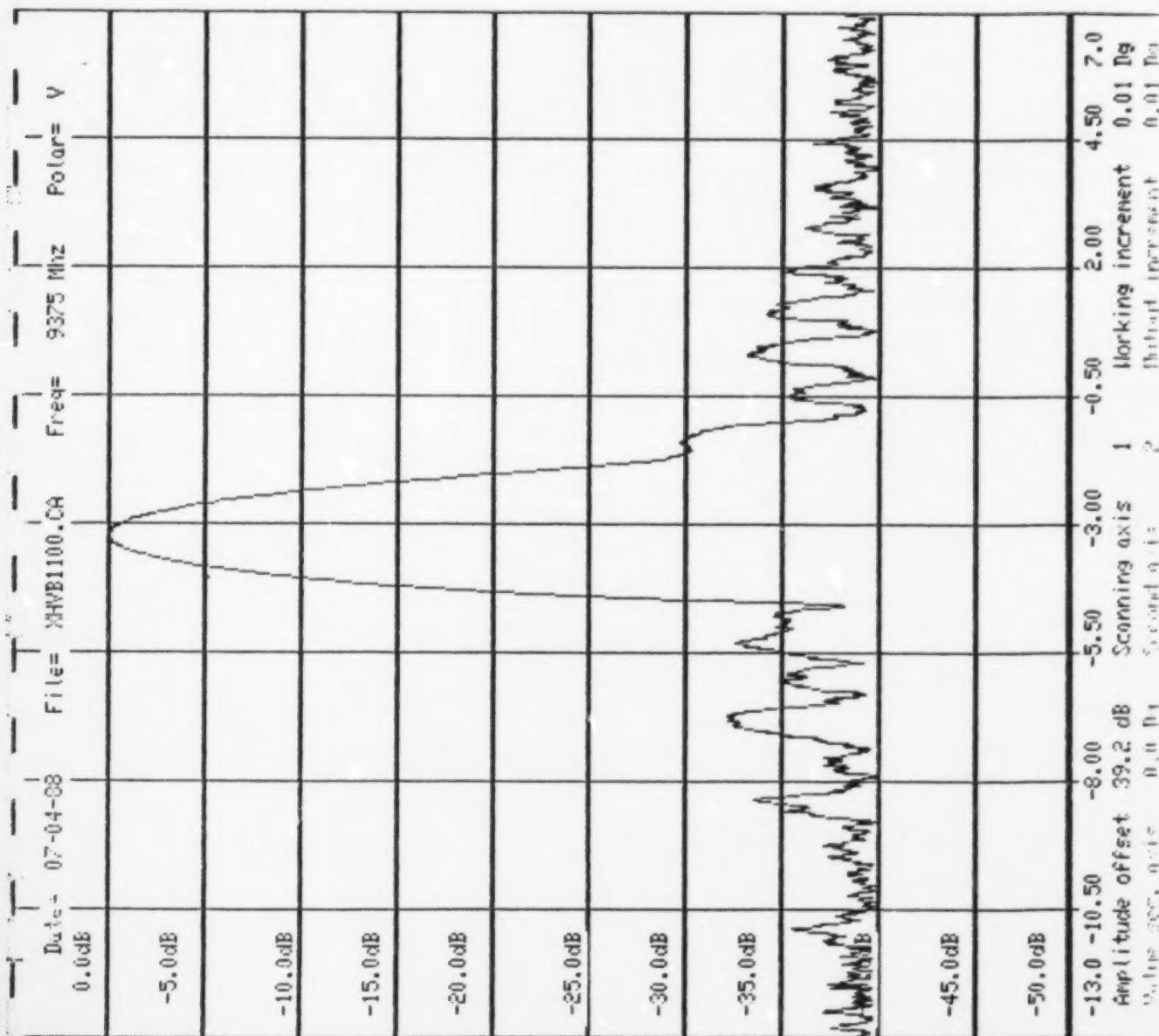
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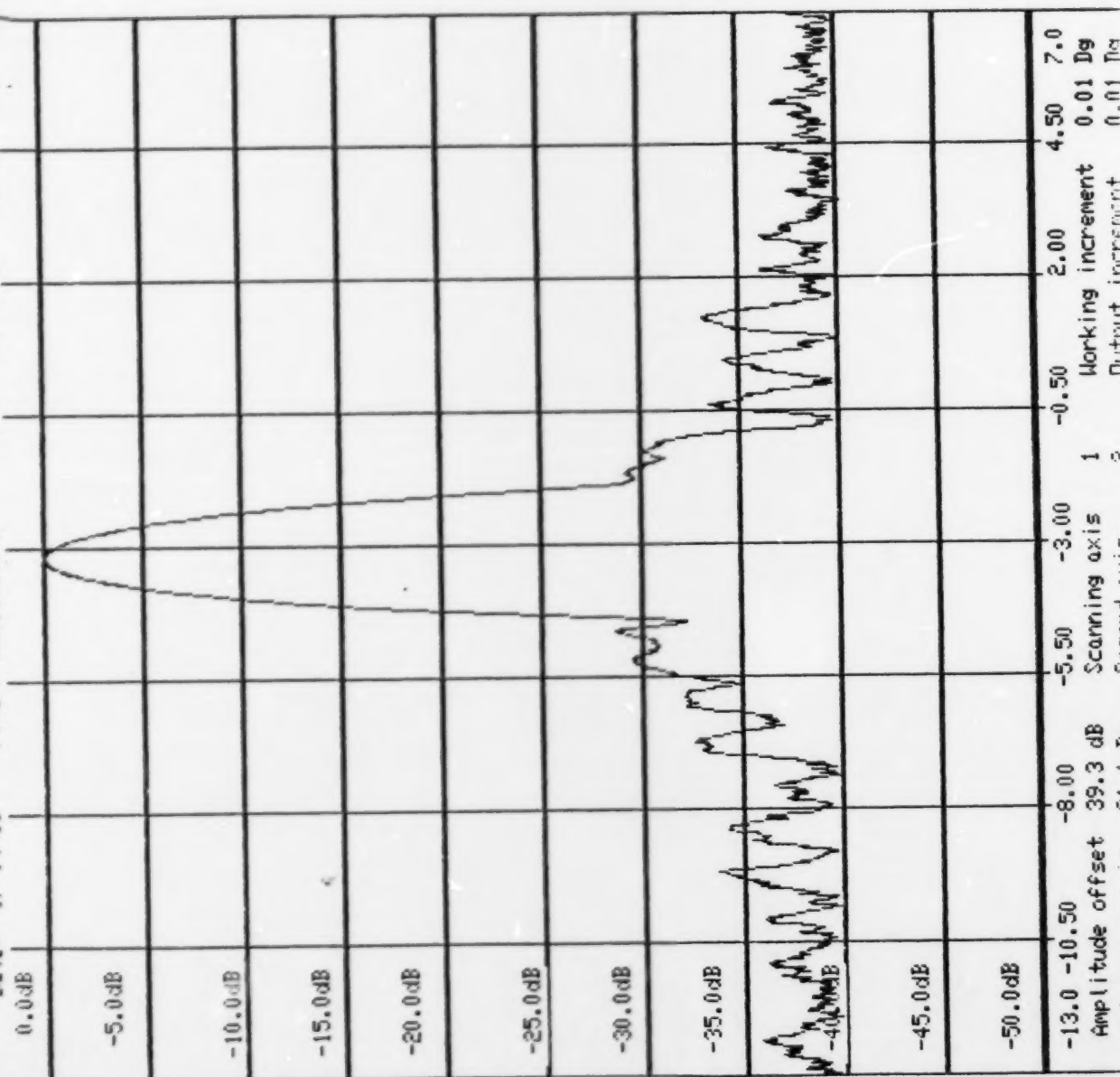








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